Enhancing the Automotive E/E Architecture Utilising Container-Based Electronic Control Units

PhD Thesis

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Declaration of Authorship

I, Nicholas Ayres, declare that this thesis entitled Enhancing the Automotive E/E Architecture Utilising Container-Based Electronic Control Units and its work are my own and original. It is submitted for the degree of Doctor of Philosophy at De Montfort University. The work was undertaken between October 2016 and January 2021.

Abstract

Over the past 40 years, with the advent of computing technology and embedded systems, such as Electronic Control Units (ECUs), cars have moved from solely mechanical control to predominantly digital control. Whilst improvements have been realised in terms of passenger safety and vehicle efficiency, there are several issues currently facing the automotive industry as a result of the rising number of ECUs. These include greater demands placed on power, increased vehicle weight, complexities of hardware and software, dependency on software, software life expectancy, ad-hoc methods concerning automotive software updates, and rising costs for the vehicle manufacturer and consumer. As the modern-day motor car enters the autonomous age, these issues are predicted to increase because there will be an even greater reliance on computing hardware and software technology to support these new driving functions.

To address the issues highlighted above, a number of solutions that aid hardware consolidation and promote software reusability have been proposed. However, these depend on bespoke embedded hardware and there remains a lack of clearly defined mechanisms through which to update ECU software. This research moves away from these current practices and identifies many similarities between the datacentre and the automotive Electronic and Electrical (E/E) architecture, demonstrating that virtualisation technologies, which have provided many benefits to the datacentre, can be replicated within an automotive context. Specifically, the research presents a comprehensive study of the Central Processor Unit (CPU) and memory resources required and consumed to support a container-based ECU automotive function. The research reveals that lightweight container virtualisation offers many advantages. A container-based ECU can promote consolidation and enhance the automotive E/E architecture through power, weight and cost savings, as well as enabling a robust mechanism to facilitate future software updates throughout the lifetime of a vehicle. Furthermore, this research demonstrates there are opportunities to adopt this new research methodology within both the automotive industry and industries that utilise embedded systems, more broadly.

Publications and Presentations

Conference Paper

N. Ayres, L. Deka and B. Passow, "Virtualisation as a Means for Dynamic Software Update within the Automotive E/E Architecture," *2019 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI)*, Leicester, United Kingdom, 2019, pp. 154-157, DOI: 10.1109/SmartWorld-UIC-ATC-SCALCOM-IOP-SCI.2019.00068.

Presentations

N. Ayres “Automotive Virtualisation as a Mechanism for Future Software Updates” *2018 Embedded World Expo 2018*, Nuremberg, Germany

N Ayres “Containerisation: A mechanism to provide seamless automotive software updates” 2019 Research Poster Competition, De Montfort University (1st Place poster see Appendix E)

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Abbreviations

ABS	Anti-lock Braking System
ADAS	Advanced Driving Assistance Systems
API	Application Programming Interface
ARM	Advanced RISC Machine
ASIL	Automotive Safety Integrity Level
BCM	Body Control Module
CAN	Controller Area Network
CLI	Command Line Interface
CST	Control System Transaction
DSRC	Dedicated Short Range Communications
DSU	Dynamic Software Update
E/E	Electrical and Electronic
EBCM	Electronic Brake Control Module
ECM	Engine Control Module
ECU	Electronic Control Unit
EMS	Engine Management System
GPIO	General Purpose Input Output
GPS	Global Positioning System
HIL	Hardware In the Loop
HMI	Human Machine Interface
IPC	Instructions per Cycle
LED	Light Emitting Diode
LiDAR	Light Detection and Ranging
LIN	Local Interconnect Network
LTE	Long Term Evolution
MIL	Model In the Loop
MOST	Media Orientated System Transport
OEM	Original Equipment Manufacturer
OS	Operating System
OtA	Over the Air
P2P	Point to Point
PCM	Power Control Module
PIL	Processor In the Loop
PSS	Proportional Set Size
r/min	Revolutions per Minute
RISC	Reduced Instruction Set
RSS	Resident Set Size
SIL	Software In the Loop
USB	Universal Serial Port
USS	Unique Set Size
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VM	Virtual Machine
VMM	Virtual machine Monitor
WLAN	Wireless Local Area Network

Chapter 1 Introduction

1.1 Motivation

Since its introduction to a mass market in the early 1900s, the motorcar changed little in principle until the late 1970s. For nearly 70 years the car was solely considered a mechanically connected, operated and monitored system. To enable a vehicle to move, manoeuvre and stop, required physical driver inputs through physical linkages connected to various vehicle components. Today, the motor car cannot be considered a solely mechanical device because of the introduction of the automotive embedded system. Embedded into various automotive subsystems throughout the modern motor car is a multitude of computer-based hardware and software, commonly known as the Electronic Control Unit (ECU). An automotive ECU similar to an embedded system is a "union of computer hardware and software" fused into a physical system (Edwards et al., 1997). Over the past 40 years, since their introduction, advancements in electronics, especially embedded computing technology, has extended ECU use into every facet of the vehicle. This widespread use includes, but is not limited to, the vehicle's engine, suspension, braking, passenger safety and comfort. Specific motor vehicle models now incorporate more than 100 ECUs often interconnected through several automotive networks providing thousands of vehicle and passenger related functions (Petri et al., 2016). The driving force behind consumer vehicle choice and purchase is no longer fuel efficiency, vehicle range or performance, rather, in-car technology is now the main motivating factor influencing consumer choice (Breitschwerdt et al., 2017).

The automotive Electrical and Electronic (E/E) architecture has matured from simple single-function microprocessor equipped hardware to multiple networked multicore systems, managing all aspects of the vehicle's operation and human-machine interactions. As more mechanical systems are digitised, they undoubtedly promote safety and operational efficiency, but this provisioning is at the cost of continual increases of computing hardware and software dependencies. The constant growth of technology within the automotive E/E architecture adversely affects system and software development and implementation

and integration costs. However, cost is not the only concern with increasing technology use. Software has become a vital and intrinsic component of the modern motor car.

The automotive industry is rapidly adopting autonomous driving features and functions which promote vehicle occupant safety and lower the increasing global levels of vehicle-related accidents, injuries and deaths (World Health Organization, 2018). Vehicle autonomy requires even more computing technology, adding to an already burdened automotive E/E architecture. To address hardware and software challenges facing the automotive E/E architecture and the automotive industry as a whole requires a new approach to providing ECU functionality. The evolution of the automotive E/E architecture can draw many parallels with the traditional datacentre. Within a datacentre, clients access systems and services from dedicated servers. This arrangement is comparable to the modern motor car where sensors and actuators are the clients sending and receiving data to and from ECUs, which are analogous to servers. The traditional datacentre has historically endured ever-increasing numbers of underutilised hardware, where new business functions often require a dedicated server to meet demand (Scheepers, 2014; Rolik et al., 2017). Like the automotive E/E architecture, the traditional datacentre has suffered from several issues, including hardware decentralisation, rising hardware implementation and operational costs, space constraints and increasing complexity. A technology that has addressed many of the shortcomings of the datacentre is the introduction of virtualisation. To promote system consolidation, multiple independent automotive functions need to merge with fewer hardware devices. Thus, a new approach to the automotive E/E architecture, similar to a datacentre model, is required. This empirical research explores how a specific lightweight virtualisation technique can be deployed within the automotive E/E architecture, addressing many of the current identified hardware and software issues and providing a standardised mechanism to promote continual software updates throughout the vehicle's lifetime.

1.1.1 Lightweight container-based ECUs

Although not a new technology, full system virtualisation is slowly being incorporated into the modern motor car and offers several key benefits to the automotive E/E architecture. These benefits include the security and separation of different automotive ECU based functions on shared computing devices within

the vehicle. The main area where virtualisation is currently employed within the automotive E/E architecture is within the human-machine interface (HMI), otherwise known as the vehicle head unit. The HMI is a device shared between two different and distinct vehicle functions: occupant entertainment and vehicle subsystem monitoring and configuration. Within this context, it offers a robust and secure separation of specific vehicle functions (Campagna and Violante, 2012). However, this virtualisation technique is not a suitable technology in ECU consolidation. Fundamentally, full system virtualisation is a virtual representation of a complete computing system. Both hardware and software are emulated into a virtual machine (VM) managed by a hypervisor or virtual machine monitor (VMM). The system resource overheads required to support full system virtualisation are well documented (Walters et al., 2008; Padala et al., 2008; Aguiar and Hessel, 2010; McDougall and Anderson, 2010; Campagna and Violante, 2012; Bermejo and Juiz, 2020; Bermejo et al., 2019). However, to facilitate ECU consolidation more, ECUs need to be brought within the sphere of virtualisation. Full system virtualisation is not ideal for embedded systems primarily due to the limitations in available system resources.

A virtualisation technology that offers considerable potential to the automotive E/E architecture is operating system virtualisation, better known as containers or containerisation. Unlike full system virtualisation where a program in execution can see all of the virtualised system resources, the same program executing within a container can only access the devices or resources explicitly assigned to it during creation. A container-based ECU must support an automotive function by providing the same level of service employed in the standard native hardware/software execution of that function. This research evaluates the suitability of container-based ECUs within the modern automotive E/E architecture. Firstly, it will investigate the specific system hardware and operating system (OS) kernel resources required to support an ECU based automotive function within a container environment. Secondly, a custom system resource testing methodology will be defined and used to evaluate this virtualisation technology. To test a container-based automotive function, a custom hardware testbed will be constructed. This will include several general-purpose computing devices similar in hardware architecture to an automotive ECU and several specific hardware peripherals. This testbed will be used as a basis for modelling an automotive central locking mechanism function. A series of utilisation, saturation and duration tests will be performed

to record and evaluate key system resource metrics across individual containers and the complete simulated automotive function. Subsequently, this research will investigate how OS virtualisation can be deployed as container-based ECUs to enhance the automotive E/E architecture through ECU consolidation. A series of CPU, memory and Input-Output (I/O) stress tests will be conducted against the execution of a control software program in native and container execution modes to understand the effect on program execution. Ultimately, this research will determine the most suitable types of CPU, memory or I/O bound containerised automotive functions that can be consolidated onto single platform ECUs to promote ECU consolidation and all the potential benefits that entail.

1.1.2 Software integration through container-based ECUs

This research demonstrates that software is as vital as any significant physical element within the modern motor car. According to Haghighatkhah et al., (2017) "over 80% of innovations in the automotive industry are now realised by software-intensive systems". Over 100 million lines of software code across 100 ECUs can be found within the automotive E/E architecture of many modern motor vehicles providing vehicle functions from engine management to passenger comfort (Petri et al., 2016; Breitschwerdt et al., 2017). These diverse functions make the modern motor car one of the most software-intensive systems we use in our day-to-day lives (Coppola and Morisio, 2016; Petri et al., 2016; Riggs et al., 2018). There are regular and periodic preventative and proactive maintenance procedures of a vehicle's physical components throughout its lifetime (Levitt, 2003). However, the same statement cannot be said concerning automotive software. Despite the requirement for reliable software, bugs and errors are unintentional but appear frequently within software code (Hangal and Lam, 2002; Onuma et al., 2016). How and why software code contains errors and flaws are varied (Noergaard, 2005; Ebert and Jones, 2009; Heiser, 2009). Problems are often introduced during the various stages of the software lifecycle. For example, bugs and errors in software code can lead to unexpected results in the output of software-driven devices and functions. This research will examine the current practice of automotive software updates and their specific associated inadequacies.

A container-based ECU automotive E/E architecture can address many of the current software update issues. It can provide a scalable and updateable solution that is not dependant on many applications of individual hardware systems, which is the standard practice in current automotive E/E architectures. In addressing the deficiency in automotive software updates, this research identifies several potential automotive software update modes that can provide a software update mechanism to enable continuous software deployment throughout the vehicle's lifetime. A series of tests will be conducted utilising the container hardware testbed which will demonstrate how container-based ECU functionality can be altered, enhanced and updated and the specific download and update times required to complete an update of a particular ECU system.

1.2 Research Questions

This thesis will investigate four broad research questions:

- *What are the specific differences in system hardware resource use of container-based ECUs compared with current native ECU execution?*
- *The most suitable process types that can be consolidated on to a single container-based ECU*
- *How can container-based ECUs facilitate a robust software update mechanism?*
- *What are the specific software update procedures and benefits provided by container-based ECUs?*

1.3 Original Contributions

This research advances current knowledge and understanding by making the following novel contributions:

Contribution 1: The novel use of container-based virtualisation techniques to support ECU software functionality.

Contribution 2: A detailed study of the specific container system resource use focusing on CPU and memory utilisation and saturation, to enhance understanding of the additional resources required to support a container environment on small computing devices. This research will extend the work on performance evaluation and discussion surrounding containers and the Internet of Things (IoT) devices presented by Krylovskiy, (2015) and Xavier et al., (2013) in their work entitled "Performance Evaluation of Container-Based Virtualization for High Performance Computing Environments".

Contribution 3: A generic automotive testbed system that can be used to test container-based ECU functionality against a novel testing methodology. This contribution extends the work on physical testbed research by Hurst, et al., (2017) and the work presented by Johnston and Cox (2017) surrounding the Raspberry Pi as a prototyping platform and host for container virtualisation.

Contribution 4: Currently, there is limited research exploring multiple memory, CPU and I/O bound processes running within containers and how these affect overall container performance. The research will

demonstrate the most suitable container combinations that can be hosted on a single small computing device.

Contribution 5: There is currently no standardised automotive software update mechanism. Furthermore, the process is often ad-hoc depending on the manufacturer and vehicle model. This research evaluates three identified modes of automotive software updates associated with a container-based ECU.

1.4 Thesis Outline

This thesis will be organised around the following themes:

- **Chapter 2** Research Background

  This chapter details the automotive ECU, including a chronology that provides context to the first ECU use and how they are currently being utilised within the modern automotive E/E architecture. It will investigate some of the specific considerations involving automotive ECU design and how they have shaped and influenced the automotive ECU architecture. Subsequently, it will provide an overview of the main types of ECUs found within the modern motor car and their organisation. The chapter also highlights many of the benefits ECUs provide to the vehicle's operation and its occupants.

- **Chapter 3** Automotive E/E Architectures: Current Issues and Complexities

  The first part of this chapter provides an overview of the issues and concerns facing the modern automotive E/E architecture in the 21st century, also identifying sources of complexity found within the automotive E/E architecture. The second part of this chapter divides the identified issues and complexities between automotive hardware and software and explains the specific associated problems. The chapter concludes with an overview of current automotive software update procedures and practices and how these apply to automotive hardware and software.

- Chapter 4 Automotive Virtualisation

  This chapter proposes the use of virtualisation to address the issues identified in chapter 3. It provides an overview of the different types of virtualisation technology available and the specific benefits virtualisation can offer the automotive E/E architecture. This chapter also examines how container-based virtualisation is a crucial virtualisation technique that addresses the challenges and complexities raised in chapter 2.

- Chapter 5 Container System Prototype

  Firstly, this chapter will provide an overview of the design considerations necessary to implement a modelled automotive function within an environment for testing the suitability of container virtualisation. It will then present the rationale for modelling a vehicle central locking mechanism and the various ECU types involved in providing this functionality. The interaction between the various system components is detailed in several diagrams. A detailed description is also provided of the necessary hardware and software required to model this function and the different mechanism trigger functions.

- Chapter 6 Resource Evaluation

  This chapter evaluates the research undertaken as part of this thesis. The proposed automotive central locking function is modelled within the testbed in two distinct modes of operation: native and container. The specific system resources required to support each of the operational modes are measured utilising several software tools. A complete list of the software tools used and the specific metrics they measure are provided. The chapter initially investigates two critical resource use metrics - CPU saturation and utilisation - and how these are affected during each test mode operation. Following CPU resource testing, the chapter examines overall memory saturation and utilisation. The chapter then explores the specific resources required to support the automotive function whilst running within a container ecosystem. Finally, the chapter investigates container performance whilst artificial hardware resource stress loads are applied to understand the effects on overall resource use and program execution timing.

- Chapter 7 Software Updates

  This research identifies several issues concerning the increasing use and dependency on automotive software to provide vehicle and occupant functionality. How new, updated or modified software is deployed to a target vehicle is a problematic area of concern within the automotive industry. This chapter will investigate the benefits that container virtualisation can bring when addressing automotive software updates. The first section will look at the recognised mechanisms of automotive software re-flashing. The chapter will then define three suitable modes of container-based software updates and the associated vehicle operational states. Dynamic Software Updates (DSU) will be investigated, including the benefits and factors to consider when using this technique. The chapter concludes with a series of test cases detailing the time taken to start, checkpoint and restore various sized containers from their associated images.

- Chapter 8 Conclusion

  This final chapter summarises the research undertaken and revisits the original contributions. Lastly, it proposes a series of areas for further associated research.

Chapter 2 Research Background

Research Background

Objectives

- Provide an overview and chronology of automotive embedded systems.
- Describe the design considerations of automotive ECUs.
- Investigate current automotive ECU architectures.
- Provide an overview of ECU types and automotive domains.

2.1 Introduction

This chapter introduces the embedded system within an automotive context and provides a chronology of the principal automotive embedded system evolution stages. The various aspects and considerations of automotive embedded system design are then highlighted before investigating the architectural hardware characteristics and associated software of the automotive embedded system and their related functions. Subsequently, this chapter provides an overview of the different embedded systems and automotive domains found within the modern motor car. Finally, it lists some of the benefits that ECUs have brought to the automotive E/E architecture. Figure 1 is a typical example of a modern automotive ECU.

Figure 1: A typical automotive ECU (ECU Technologies, 2014)

2.2 Chronology of Automotive Embedded Systems

In similar respects to embedded systems, automotive ECUs are computing-based systems fixed within a piece of equipment within the car to monitor and control a particular function (Takada, 2012). ECUs perform these tasks and functions repeatedly, often in real-time and within the harsh operating environment of a functioning motor car where they are subjected to extreme external environmental effects. During regular operation, a running motor car produces heat through combustion and vibration from engine operation and movement. ECUs are exposed to external influences through atmospheric conditions and G-Forces from the vehicle's acceleration and braking. Any ECU design must cope with these conditions without impacting system performance or adversely affecting the designed task or function.

2.2.1 ECU chronology

In 1977, General Motors released the Oldsmobile Toronado (Bereisa, 1983), which is regarded as the first car to include a microprocessor-based ECU. This first ECU implementation managed the electronic spark timing (Charlette, 2009) of the combustion process. According to Takada (2012), since their introduction in the late 1970s, the ECU has gone through several evolutionary stages.

Stage 1 Basic Digitisation (the Late 1970s)

Independent computer controls were applied to various separate vehicle components including the engine, brake and steering subsystems. These electronic systems were simple P-channel metal-oxide-semiconductor serial CPUs. The car was still principally under mechanical control with little to no communication between computing devices.

Stage 2 Increasing Digitisation and Simple Communication (the Mid 1980s)

Mechanical chassis and engine control moved towards computer control throughout the 1980s. Many previously mechanical and hydraulically linked subsystems were replaced and controlled by software-driven actuators in an x-by-wire system between driver input and vehicle output (Coppola and Morisio, 2016). These systems included:

- Engine Control Module (ECM) – controls several engine related actuators to ensure peak performance.
- Transmission Control Unit – optimal automatic and semi-automatic gear changing.
- Anti-lock Braking System (ABS) – prevents the wheels from locking under excessive braking.
- Body Control Unit – includes systems associated with passenger comfort.

Computer assistance provided increased efficiency (Work et al., 2008). New software-based subsystems often required hard real-time performance with the caveat of safety-critical constraints. Figure 2 represents a mechanically connected turbo mechanism and the more recent ECU connected system.

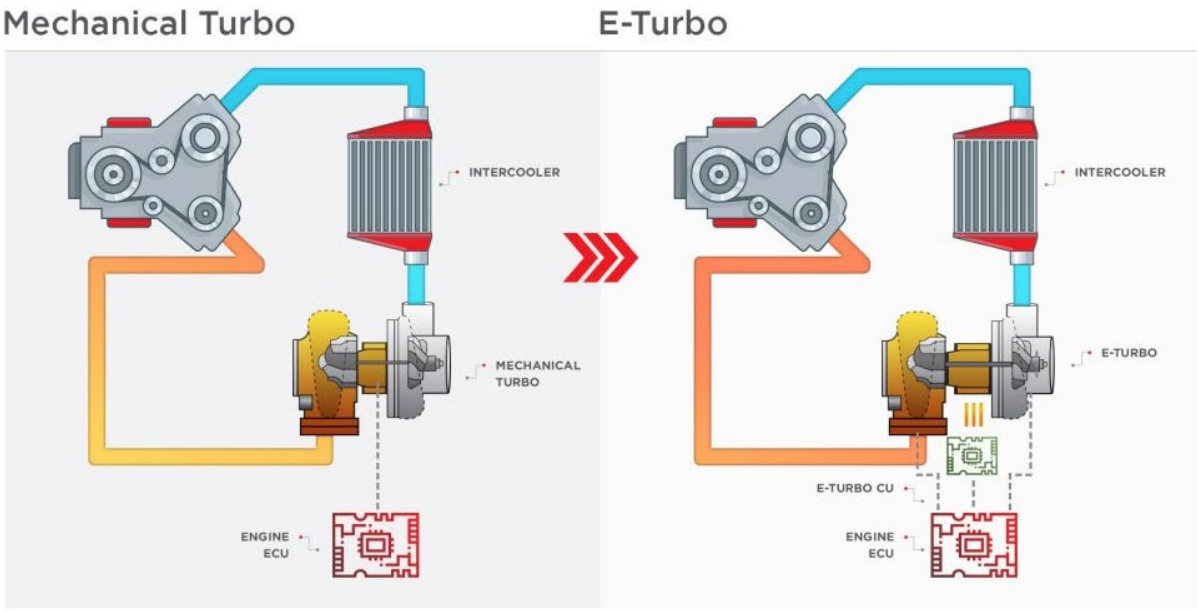


Figure 2: Mechanical vs digital control (Garrett Advanced Motion, 2019)

Stage 3 Integrated Systems and Services (the Late 1980s to 2000)

Independent and isolated ECUs exchanged data with other systems through physically connected links known as point to point (P2P) connectivity routed through the vehicle's existing wiring harness (Navet and Simonot-Lion, 2009). The inclusion of more computing hardware into the automotive E/E architecture placed high communication demands on the P2P network. The increasing use of ECUs and their information exchange requirements resulted in an overly complicated and cumbersome automotive E/E architecture. To alleviate some of the problems surrounding P2P connections, in the mid-1980s, Bosch developed the Controller Area Network (CAN): A "high-integrity multi-master [128 node] serial bus system for networking intelligent devices" (National Instruments, 2014). The BMW 8 Series in 1988 was the first motor vehicle to incorporate this new automotive networking technology. By the early 1990s, the CANbus quickly became the automotive industry-standard for in-vehicle networking, primarily due to its simplicity, low cost and high connectivity. During the 1990s, software-based functions extended from critical and operation vehicle functionality to passenger comfort and entertainment. Previously isolated entertainment systems were integrated into multimedia systems providing infotainment functions and connectivity to external multimedia devices.

Stage 4 Increased Safety and System Innovation (Current Vehicle Development)

ECU development is starting to move away from single computer-based automotive innovations to full system innovations requiring higher interoperability and information exchange levels to provide a multifaceted system.

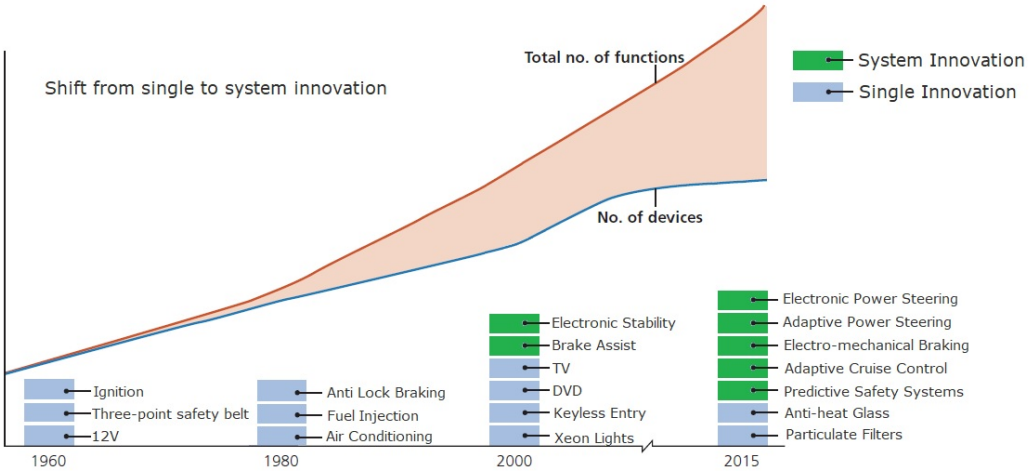


Figure 3: Shift from single to system innovation (Dannenberg and Burgard, 2015)

Since the start of the new millennium, safety has been pushed to the forefront as the number of vehicles has increased globally, as have associated road-related accidents and deaths. In Europe, human error is attributed to 90% of all vehicle-related accidents (Brookhuis et al., 2001). With massive increases in deaths connected with vehicle use, there has been a focus on ECU controlled automotive safety systems.

Stage 5 Fully Integrated Autonomous Vehicles (the Future)

As the motor car enters the autonomous age, safety will move into Advanced Driver Assistance Systems (ADAS). Autonomous vehicles require vast external sensor data from imaging systems including Light Detection And Ranging (LiDAR), radar and video to enable the car 'to see' its surroundings so it can respond to a rapidly changing environment. These systems rely solely on ECUs to provide all functionality as well as vehicle subsystem integration. The vehicle will be a fully integrated digital system with no mechanical backup. Through a fully ECU integrated system, the car for its entire journey will operate with or without vehicle occupants or operator interaction.

2.3 Automotive ECU Design Considerations

General-purpose computing design reflects a modular architecture and incorporates the fastest processor possible. The importance and focus of embedded systems, including automotive ECUs, are not necessarily on performance but also reliability and dependability (Koopman, 2004). There are many ECUs within modern motor vehicles realising all manner of vehicle-related tasks, not just the primary function (vehicle operation) but passenger comfort and entertainment that require their own dedicated ECUs. Embedded devices characteristically have tight functionality and implementation constraints, including:

2.3.1 Guaranteed real-time operation

Many vehicle-related functions, such as the engine combustion process, are a sequence of real-time operations that require real-time data. Confirmation of optimum engine operation requires certain guarantees where individual Engine Management System (EMS) tasks and processes are scheduled and executed with real-time deadlines (Gajski and Vahid, 1995).

2.3.2 Weight limitations

According to Abinesh et al. (2014), 30% of a vehicle's weight is attributed to its electronics. Higher overall weights result in higher fuel use and lower fuel efficiency. Poor performance in engine operation inevitably produces higher CO_2 emissions in fossil fuel burning engines or a potential reduction in overall range in a hybrid or fully electric-powered vehicle (Onuma et al., 2016).

2.3.3 Size limitations

ECU size is an essential factor for consideration within the car. Space for the ECU is dictated by the vehicle's overall size. ECUs often reside near the components they manage and their size can be influenced by the constraints of individual vehicle space and aesthetics.

2.3.4 Optimising power consumption

ECUs, like all computing technology, require the consumption of electrical power for operation, which is provided by the vehicle’s internal power systems. Embedded systems, by design, must conform to low

power consumption when compared with general-purpose computing. According to Otani, et al., (2019) “the power consumption of automotive MCUs [Microcontroller] must be single-digit Watts”. However, the more systems incorporated within the automotive E/E architecture will inevitably result in higher overall power consumption.

2.3.5 Safety and reliability requirements

Safety is "freedom from those conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment" (Leveson, 2011). Reliability is "the ability of a system or component to perform its required functions under stated conditions for a specified period of time" (Government Accountability Office, 2009). Safety and reliability are not necessarily interchangeable – a safe system is not necessarily a reliable one. Automotive safety is measured using the ISO26262 standard, which defines several Automotive Safety Integrity Levels (ASIL) depending on the responsibility of the systems within the car. An event is measured against its severity, exposure and controllability and an appropriate ASIL level is applied (Takada, 2012).

2.4 The Automotive ECU Architecture

ECUs, similar to other embedded systems, have several layers of hardware, firmware and software which establish its overall architecture. Individual ECU layers include an upper application layer that provides functionality. This functionality is supported by the underlying hardware which stores, processes and manipulates data. Figure 4 depicts a typical ECU architectural layout.

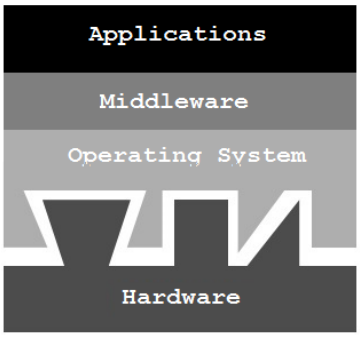


Figure 4: Typical ECU hardware/software architecture

2.4.1 Application software layer

Application software is essentially a computer program consisting of a set of tasks and routines. These programs can be single functions which perform a single simple task such as opening or unlocking the vehicle doors. At the other end, there are highly complex, safety-critical applications involved in monitoring and controlling multifaceted tasks such as engine function and management.

2.4.2 Middleware layer

The middleware layer, often referred to as a general-purpose service, sits between the top-level applications and the underlying platform interface (Bernstein, 1996). In this context, Bernstein (1996) defines a platform interface as a "set of low-level services and processing elements", which also includes the operating system. Expanding on this, Krakowiak (2003) states that middleware provides services to the application software layer when the operating system cannot offer those required services. Middleware hides the heterogeneity of the ECU's underlying hardware components from the upper application software (Shan, 2006).

In an automotive ECU context, Broy et al. (2007) propose that middleware addresses the following key issues:

- Hiding application distribution.
- Hiding OS hardware and communication protocol heterogeneity.
- Supplying standard services for application collaboration.
- Reusability.

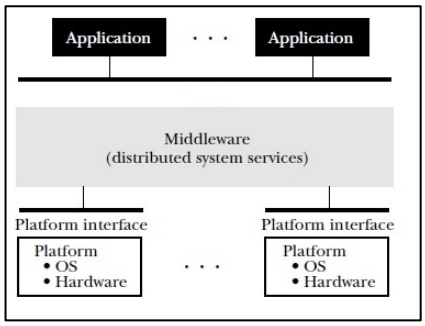


Figure 5: Middleware (Bernstein, 1996)

2.4.3 Operating system layer

An embedded OS has the responsibility of executing tasks, memory management and providing a communication interface (Wild et al., 2006). However, due to efficiency requirements, a one size fits all operating system is often not possible within an ECU context. Automotive ECUs need to be personalised to the required task they have been designed for (Marwedel, 2006). The automotive industry is developing more general-purpose operating systems including open source automotive-grade Linux, embedded Linux and proprietary OS examples including QNX and VxWorks. However, these OS types are aimed at more resource available systems to support HMI features and functions. To support the "under the hood" ECUs, a real-time operating system (RTOS) is often the best fit OS for the embedded system (Lee, 2006).

2.4.4 Hardware layer

ECU hardware is, inherently, a small computer but one which is specifically designed and tailored to the task it is responsible for performing. Tailoring hardware makes each ECU highly bespoke in architecture but extremely efficient in operation and power consumption. For example, an EMS ECU requires more complex real-time processing and memory requirements than a Body Control Module (BCM) that controls simple door functionality.

2.5 ECU Types and Automotive Domains

A vehicle functional domain attempts to represent the logical rather than physical distribution of ECU hardware and vehicle functionality (Sommer et al., 2013). There are many different configurations and variations of automotive domains which vary between vehicle make and model (Simonot-Lion and

Trinquet, 2009; NXP, 2013). However, there are four commonly recognised domains: powertrain, propulsion, body and chassis, and infotainment and safety (Patterson, 2017). According to Simonot-Lion and Trinquet (2009), these can be categorised as vehicle or passenger-centric:

- Vehicle-centric includes powertrain, chassis and active/passive safety systems.
- Passenger-centric includes multimedia, HMI and passenger comfort.

Grouping similar vehicle function ECUs into specific domains has numerous benefits associated with the automotive E/E architecture. These benefits include reductions in cross-functional ECU communication and a logical distribution of hardware or associated automotive functions. Any required cross-domain communication is often provided by a single or several domain gateways.

Figure 6 shows a typical ECU layout ECUs within a modern motor car, colour coded for the different automotive domains. The yellow ECUs provide vehicle occupants with entertainment and comfort features and functions. The pink ECUs relate to vehicle and occupant safety systems. The blue ECUs control various aspects of the vehicle.

Figure 6: Example ECU layout within the modern motor car (Currie, 2016)

2.5.1 Powertrain and propulsion domain

This domain is responsible for how a vehicle generates and delivers the power to the road surface. Transmission and engine management, power distribution systems and gearbox functions are primary examples of this domain (Patterson, 2017). Historically, power was solely generated through the

combustion of fossil fuels. However, due to consumer demands and environmental concerns, automotive propulsion systems are now starting to shift towards alternative power generation sources, including hydrogen, hybrid electric and fully electric systems (Sharma and Strezov, 2017). The powertrain and propulsion domain have had to adapt accordingly. For example, many sensors needed for a fossil-fuel burning vehicle are not required in an electric vehicle. ECU types within this domain include the powertrain control module (PCM) and the ECM. These ECUs are primarily responsible for engine management. Sensors distributed throughout the engine send information to the PCM and ECM, which use multidimensional performance maps, also known as lookup tables, to manipulate actuators to deliver the most optimal engine performance (Brunemann et al., 2002). Before PCM and ECM systems, parameters such as air to fuel mixtures and ignition timing were mechanically controlled through direct linkages.

2.5.2 Chassis and body domain

This domain includes all aspects of vehicle safety and passenger comfort. The main areas of automotive functionality within this domain include vehicle braking, steering and suspension. Other functionalities relate to direct passenger vehicle interactions, such as vehicle access control, lighting, cabin heating and cooling. Example ECUs include the Electronic Brake Control Module (EBCM). The EBCM improves safety through advanced braking mechanisms by monitoring the wheel state and comparing the received information with stored data maps. Observed data relating to a potential wheel lock-up initiates safety system including ABS and traction control, preventing the vehicle from wheel lock and subsequent uncontrolled skidding. The BCM is a generic term for any computer-assisted function or system, not directly related to engine function or operation. The tasks of a BCM can vary greatly depending upon the vehicle make and model. Generally, BCM functions include door relays, exterior and internal lighting systems, electric window motors and climate control.

2.5.3 Safety domain

This domain provides safety mechanisms for the vehicle as well as the vehicle's occupants. They are categorised as active and passive safety. Active safety systems continually function whilst the vehicle is in operation and aid in preventing an accident. They often have cross-functionality between the body and

chassis domain. Traditional safety functions include ABS, traction and stability control (Axelsson et al., 2003). New and emerging active safety systems include brake assist, collision warning/avoidance and intelligent speed adaptation (Braun et al., 2015). Passive safety systems deploy when an accident has been detected or triggered, for example, airbags and seatbelt pre-tensioners, which are designed to minimise vehicle occupant injuries.

2.5.4 Infotainment domain

Infotainment systems fuse information and entertainment, replacing old legacy cassette/CD multimedia entertainment systems. Infotainment is a broad and generic term for a technology which may fuse multiple features and functions including navigation, passenger entertainment, telematics and external communication. It often comes with a whole host of features displayed on a centrally mounted screen within the vehicle dashboard (Coppola and Morisio, 2016). The functionality provided by infotainment requires high software-intensive systems. It may also include an Internet or wireless connectivity solution utilising a shared personal portable communication device or connectivity technology embedded within the vehicle. Infotainment systems can stream high levels of data into the car, providing the occupants with information, music and video services.

2.6 Qualities of the Automotive ECU

Automotive ECUs have been a vital part of the modern motor car since their introduction in the late 1970s. Their use has grown over the years from single isolated instances to a multitude of interconnected devices.

2.6.1 Reliability

Generally, vehicles are expensive items and consumers expect a long life and continual use from them. Consumers' expectations of a vehicle’s life span are up to 10 - 15 years, or 150,000km travelled. These figures are not uncommon with current motor vehicle technology. Moreover, safe and consistent vehicle operational reliability over a vehicle’s life span is a fundamental requirement. Overall reliability is underpinned through dependable vehicle subsystems. ECU reliability has to be very high to support a long

vehicle life span. To support this, the automotive sector boasts an ECU failure rate of $50*10^{-9}$ failures per hour (Braun et al., 2015).

2.6.2 Dedicated function

The implementation of ECUs is often centred around providing dedicated hardware per dedicated function. By dedicating ECU hardware and software design, and implementation ensures:

- only necessary hardware is used, keeping ECU hardware costs to a minimum.
- an increase in overall system efficiency.

2.6.3 Efficiency and utilisation

ECU efficiency is derived from a particular systems hardware requirement and includes only the bare minimum components to accomplish the desired task. Peak load and performance on an ECU is predictable at design and the hardware architecture is developed to match this, resulting in a reduced ECU unit cost and energy consumption during operation. ECU technology promotes overall vehicle operational efficiency. Efficiency can be observed by reducing fuel use which ultimately reduces vehicle pollution levels and minimises vehicle operating costs (Kassakian et al., 1996).

2.6.4 Automotive function modularity

Many vehicle tasks and functions require computational power from a single simple ECU to accomplish their goals. Other automotive functionality may in the course of operation utilise several ECUs, each controlling or monitoring a specifically related subsystem to achieve a more complex function or task. Shared information is exchanged between subsystems often via in-vehicle networks linking them together to form an interconnected system. Smaller interconnected ECUs responsible for controlling their corresponding subsystems are usually less complex and inexpensive than a single extensive complex system (Wilmshurst, 2001).

2.7 Chapter Summary

This chapter provides an overview of the ECUs and how automotive E/E architecture has evolved since their introduction. The chronology has highlighted some of the significant automotive system milestones which have utilised embedded ECU computing technology. ECUs have replaced many of the mechanical linkages between driver input and vehicle output which has undoubtedly promoted efficiency and reduced pollution as well as overall vehicle operating costs. In particular, this chapter has emphasised several vital considerations when designing automotive ECUs, especially automotive functional requirements, where a combination of real-time and safety-critical data is required. A description of individual ECU architectures reveals that ECU hardware and software are often highly bespoke and designed and implemented to complete single tasks or functions. A summary of dedicated ECU tasks and functions within the car, grouped into automotive domains, has been provided along with a description relating to each domain. Lastly, this chapter has reviewed the benefits ECUs have had on the modern motor car, highlighting increased operational efficiency, comfort and safety. The next chapter investigates and evaluates the complexities of ECU hardware and software, and the issues facing the modern automotive E/E architecture on which the rest of this thesis is based.

Chapter 3 Automotive E/E Architecture: Challenges and Complexities

Objectives

- Provide an overview of the primary issues concerning the automotive E/E architecture.
- Identify the sources of complexity within the automotive E/E architecture.
- Investigate the issues associated with automotive computing hardware.
- Investigate the issues regarding automotive software.
- Provide an overview of current software update procedures and practices.

3.1 Introduction

This chapter aims to provide a detailed description of the principle issues and causes of complexity within the modern automotive E/E architecture. The structure of this chapter concerns two core topics of interest: automotive ECU hardware and software. The previous chapter detailed the benefits of ECU controlled and monitored automotive functions, however, several persistent issues face the automotive industry and the automotive E/E architecture as more technology is introduced. One of the critical problems of automotive hardware is the rising numbers of ECUs within each vehicle model and section 3.2 highlights the associated issues, including related costs, additional weight and increased power requirements. The increasing use and reliance on more and more computing technology is a factor when considering automotive E/E complexity. Overall automotive E/E architectural complexity is a growing concern and the sources of this complexity are detailed in section 3.3. Decentralisation and high levels of hardware and software optimisation are contributing factors and sources of automotive E/E architectural complexity. Increases in functionality result in an increased requirement for software. The last sections of this chapter focus on software bugs and errors, potential security threats and vulnerabilities, and the extended time frame automotive software is expected to last. The final section reviews the current automotive software update mechanisms and how they apply to the automotive industry.

3.2 Issues Associated with Automotive Computing Hardware

As embedded technology progresses, so does the required functionality of embedded systems. This has resulted in embedded technology "groaning under the weight of requirements" (Lee, 2006). With each new vehicle model, the automotive industry faces numerous challenges surrounding the inclusion of new embedded technologies (Wallin and Axelsson, 2008; Schwazrl and Herrmann, 2018).

3.2.1 Increasing numbers of ECUs

Broy (2006) stated that the upward trend of ECUs being included in the motor car was set to continue over the coming decades. This prediction has been realised, with growth seen from system digitisation, ADAS and vehicle autonomy (Reinhardt and Kucera, 2013). Figure 7 shows the predicted increase over the next decade in average ECU cost by domain.

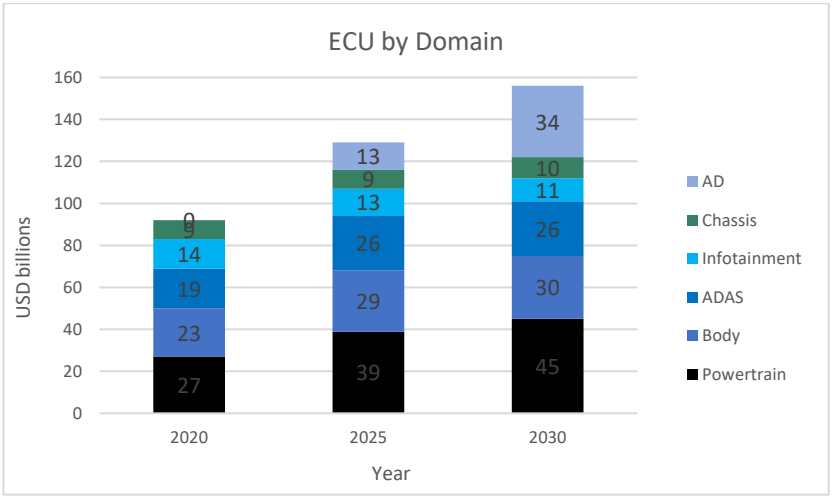


Figure 7: ECU market by automotive domain (Burkacky, et al., 2019)

The principle issues associated with the increase in the number of ECUs within the modern motor car include:

3.2.1.1 An overall increase in vehicle system development costs

The increasing use of ECU based features and functions within the modern motor vehicle results in cost increases in system development. Consequently, system development costs have escalated to levels where 30-35% of the vehicle's total cost is directly associated with its electronics and software (Shavit et al., 2007). The past and projected overall cost can be seen in Figure 8.

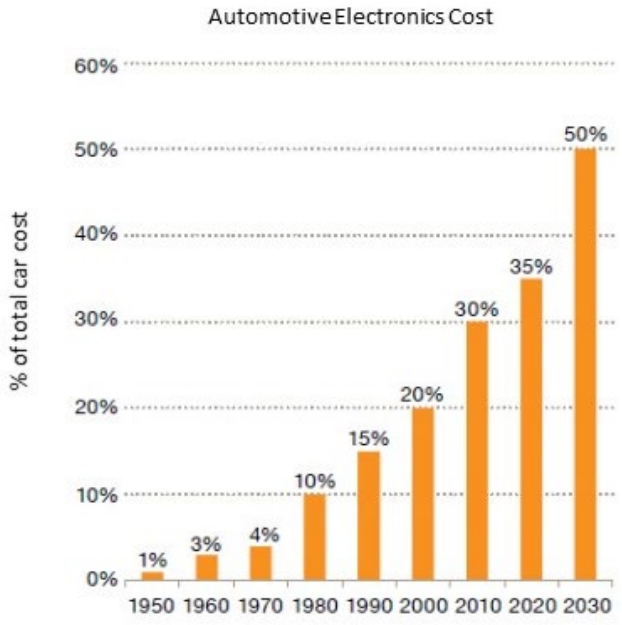


Figure 8: Automotive E/E cost compared to overall vehicle cost (Chitkara et al., 2013)

The compound annual growth rate between 2020 to 2030 for automotive E/E hardware is predicted to rise by approximately 33% from $92 billion to $156 billion. Figure 9 shows a breakdown of the main categories relating to automotive E/E hardware and the individual component cost and percentage growth.

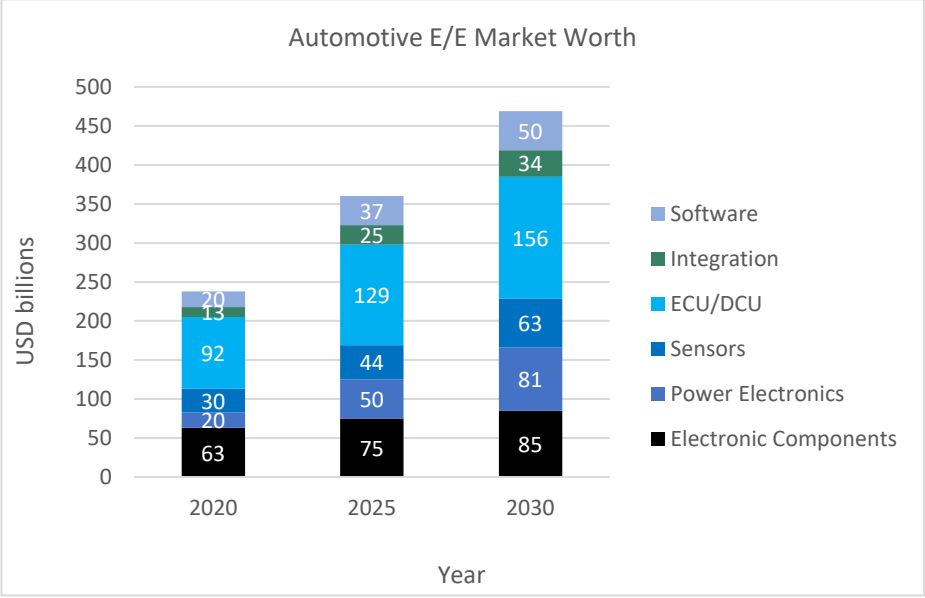


Figure 9: Automotive E/E market worth (Burkacky et al., 2019)

3.2.1.2 Growth in individual hardware component costs

Increasing numbers of ECUs increases development time and automotive budget costs (Reinhardt et al., 2013). The past and projected overall percentage cost of automotive electronics, when compared with vehicle cost, can be observed in Figure 10.

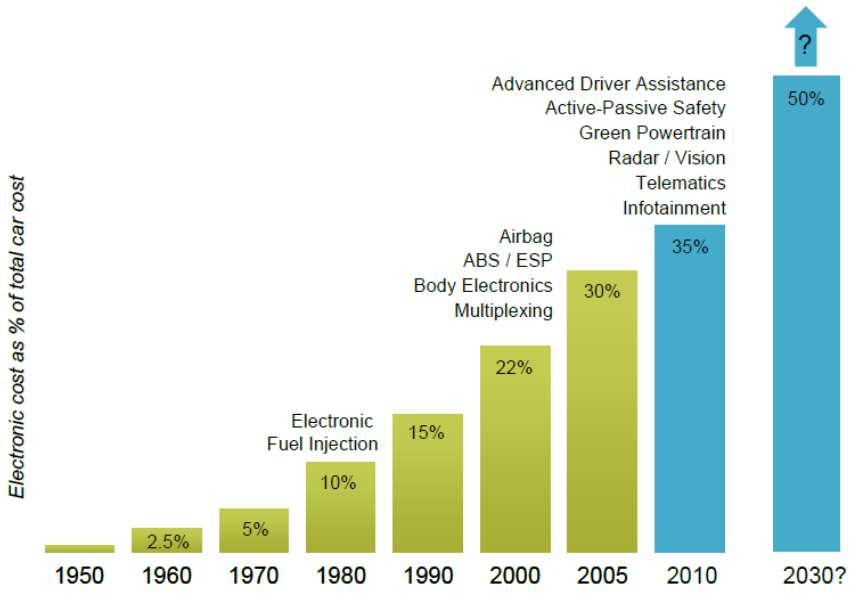


Figure 10: Electronic cost as a percentage of total car cost (Nelson, 2010)

With the increasing use of ECU based features and functions, vehicle development costs have escalated to a position where 30 - 35% of the vehicle's total cost is associated with the vehicle's electronics and software (Broy et al., 2007; Shavit et al., 2007; Automotive IQ, 2017).

3.2.1.3 Increased bandwidth requirements for in-vehicle network data exchange

Automotive networking has simplified the communication links between dedicated ECU sensors and actuators and provides a mechanism for cross ECU communication. The P2P method of inter ECU communication proved to be grossly inefficient, bulky and heavy with very limited scalability. To address the increasing issues surrounding P2P in the mid to late 1980s, the automotive industry adopted the CAN as its primary in-vehicle ECU communication. However, as the number of ECUs have grown, the total traffic loading on in-vehicle networks on the primary vehicle network, the CANbus, has dramatically increased in recent years. This simple, limited bandwidth network has become congested under the sheer volume of

demand placed upon it (Reinhardt and Kucera, 2013). To address the needs of increased bandwidth, multiple divergent in-vehicle network media and protocols are now being introduced to handle a myriad of in-vehicle communication. For example, the local interconnect network (LIN) supports simple, non-critical low priority ECUs. A LIN network often includes vehicle climate control, seat and wing mirror position motors (Ruff, 2003).

In contrast, the Media Orientated Systems Transport (MOST) network was developed to handle high bandwidth requirements demanded by video, voice and other data suited for infotainment and hi-fidelity music systems. As the demands on available bandwidth requirements increase, automotive-grade Ethernet is becoming a viable solution. Ethernet is a well-established mature communication protocol with over 30 years of operation and has become the de-facto standard in general computer networks. It can transport data at rates 100 times faster than CAN - currently, up to a 100Mb/s transmission rate can be achieved with high reliability and adaptability. It is a growing trend for in-vehicle network solutions. For example, in 2014, only 1% of new vehicle models utilised Ethernet as an in-vehicle network solution, but by 2020, Ethernet use in automotive networks is set to increase by 40% (Sawant et al., 2018).

Multiple ECU and sensor data across different domains are frequently required to achieve a particular automotive task or function. To transmit data from one network protocol to another requires additional hardware interfaces to translate messages into a suitable format. However, the increase of network media and interface hardware, adds extra weight, development and component costs.

3.2.1.4 Additional vehicle weight

The increasing reliance on computing technology within the motor vehicle requires additional ECUs, associated peripherals and supporting network media. Vehicle weight is a crucial factor in automotive operation where an increase in hardware results in extra vehicle weight, which has a detrimental effect on vehicle performance and fuel efficiency. After the engine, the vehicle's second-heaviest component is the in-vehicle network wiring. This wiring can consist of over 6km of copper wire with an approximate weight of 70kg (NXP, 2013). According to Leen and Heffernan (2002), for each additional 50kg of vehicle weight there is an increase of fuel consumption by 0.2 litres per 100 kilometres travelled. With a modern motor

vehicle expected to travel an estimated 250,000km operational range, this equates to an additional 500 litres of fuel over its lifetime.

3.2.1.5 Power consumption

Additional computing hardware technology consumes more power, which in the motor car is of a limited quantity unless extra fuel (electrical or fossil-based) is consumed to generate additional power. Schmutzler et al., (2012) suggest there are three associated problems with the increased use of automotive power:

- An overall increase of engine emissions within fossil fuel-burning vehicles
- A decrease in operational range, similar to an increase in vehicle weight
- Unnecessary power consumption due to continuous power supplied to ECUs, even ones which have no operational functionality depending on the vehicle's current state

Figure 11 below highlights power consumption concerning increasing ECU numbers.

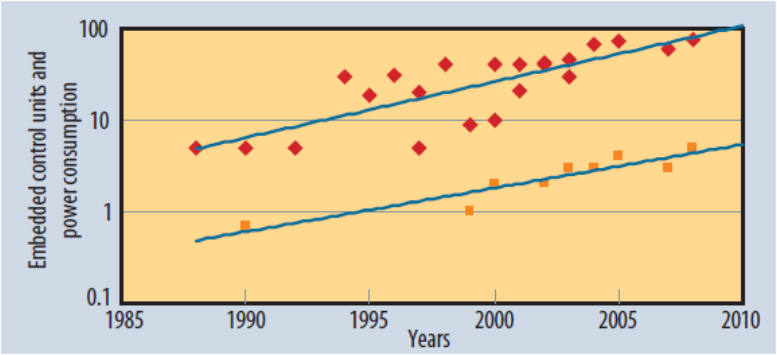


Figure 11: ECU power consumption (Ebert and Jones, 2009)

Tiwari, et al, (1994) evaluate the average power consumed by a microprocessor while running a program as:

$$E = (I * Vcc)(N * \tau) \quad 1.1$$

E Energy consumed by a program

I Average current for an instruction sequence

V_{CC} Supply voltage

N Number of cycles taken to execute

τ Time

Electrical power generation is accomplished in fossil fuel burning engines, commonly known as the vehicle alternator. The primary function of this equipment is to maintain the vehicle's battery charge level and provide power to its electrical system. However, the additional electronic components that must be installed increase the total power requirement - alternator output or capacity must be improved to meet this extra demand. An alternator requires a certain number of engine revolutions per minute (RPM) to generate enough charge to meet the vehicle's electrical system requirements, causing an increase in engine CO_2 emissions. In stark contrast to a fossil fuel burning vehicle, electric cars derive power for their propulsion from an internal battery system. The battery system in an electric vehicle must also power the subsystems included within the automotive E/E architecture. Excessive ECU power consumption must be kept to a minimum to preserve the vehicle's overall range (Reinhardt and Kucera, 2013).

Another pressing issue with ECU power consumption is the practice of continually powering ECUs within the entire E/E architecture during vehicle operation. Many ECUs only operate under particular or exclusive circumstances but are often powered up from the vehicle's initial start until the vehicle is powered down. There is usually little consideration to placing these situational ECUs into a suspend or a temporary power-down mode until required. According to Esch et al. (2012), "the boot lid ECU function is only needed for 3% of total vehicle activity time. During the remaining 97%, electrical energy is merely consumed unnecessarily".

3.3 Complexities

Vehicle functions are governed by hardware and software, often requiring data transmission through in-vehicle networking solutions. Both Furst (2010), and Braun et al. (2015), agree that the principal causes of automotive E/E architectural complexity are the continual increase and use of computing hardware technology, associated software and in-vehicle networking solutions. Over the coming decade, the modern motor car will see an influx of ADAS and vehicle autonomy functions. These emerging technologies will considerably increase the amount of embedded software within the modern motor car.

3.3.1 Architectural decentralisation

One of the causes of system complexity is a decentralised automotive E/E architecture. Many vehicle functions and operations cannot be realised by a single ECU and its associated peripherals. Vehicle functions are often disseminated across several ECUs located throughout the vehicle (Kanajan et al., 2006). To accomplish many vehicle functions and tasks, data is transmitted between multiple peripherals and ECUs (Wallin and Axelsson, 2008). For example, depending upon vehicle make and model, a door central locking function activates via several different trigger mechanisms, including the vehicle key fob or current vehicle speed. These two triggering mechanisms reside across very different automotive domains, requiring cross-domain communication to the central locking/unlocking function. With the recurrent increases in automotive functionality, cross-domain interaction will inevitably grow, which will lead to higher architectural complexity through ECU and automotive function decentralisation.

3.3.2 Hardware and software optimisation

The inclusion of more technology into the automotive E/E architecture inevitably results in higher costs. ECU hardware is often highly optimised to address these rising costs (Broy et al., 2007). Embedded systems usually have a configuration which is fixed during the hardware design stages (Belaggoun and Issarny, 2016). To reduce overall ECU costs, embedded hardware must be optimised and include the bare minimum and necessary components to complete the required ECU task or function. However, additional components result in a higher overall cost of the vehicle. Even the smallest additional component can incur considerable costs when factoring the number of vehicle models by the total number of vehicles produced over that vehicle model's lifetime. Broy et al., (2007) suggest that an additional hardware cost of €1 on a single component over 500,000 units per year would yield additional costs of €3,500,000 for the lifespan of a vehicle model production of seven years. High ECU hardware component optimisation produces a rigid, bespoke design where hardware reusability between vehicle models is often not viable.

High levels of hardware optimisation inevitably lead to necessary software optimisation. High levels of software optimisation have resulted in several additional adversities including:

- Increased software complexity.
- An increase in the number of code defects due to optimisation.
- A lack of software reusability.

Software code is written and subsequently optimised to the precise hardware specification (Broy et al., 2007). High levels of software code optimisation can lead to software defects. The codebase footprint may require certain levels of optimisation to fit within limited system resources including storage, memory and processing capability. Software code must be able to complete the task it is designed and coded for, and ensure code execution requirements do not exceed the limits of available hardware resources. The number of software functions per ECU is often restricted due to the confines of available system resources, including memory and processing capabilities (Törngren et al., 2009). High software optimisation and specific limiting hardware architectures make software reusability difficult or, in some cases, impossible when trying to port new and updated code to target hardware (Haghighatkhah et al., 2017). Broy (2006), stated that after just three years, the automotive industry experienced discontinuation rates of 20 - 30% of a vehicle model's ECUs. This relatively short hardware lifespan results in software having to be re-integrated into the system. Due to high levels of hardware optimisation software, portability and reuse is a problem for the automotive industry.

3.4 State of the Art Hardware

The automotive industry has faced many challenges since the introduction of the ECU. There have been many solutions that the automotive industry has implemented or researched to address these issues and complexities of the automotive E/E architecture. For example, to promote ECU consolidation, System on Chip (SoC) integrates many complete system components into a single integrated circuit (Yamada and Kimura, 2020). However, this technology is still bound by the same limited resource constraints as current ECU hardware, which is a problem when addressing automotive software updates. Field programmable gate arrays is a technology being adopted by the automotive industry but focuses on infotainment and

video and image processing applications associated with ADAS features (Oh et al., 2019). This technology can be reprogrammed, which can provide a mechanism for supporting possible future software updates. However, they are expensive in a mass production environment and require higher levels of power consumption. Consolidation is also currently being researched at the domain level utilising automotive domain controllers, which are much larger resource capable computing devices that can host multiple ECU functionality on one system (Wang and Ganesan, 2020). However, these are all hardware-based solutions that often still utilise embedded hardware. Constraining automotive functionality on the hardware level does not promote a flexible software architecture, especially when software must be periodically updated to address a software associated issue.

3.5 Software Associated Issues

Vehicle software is considered a significant component of the modern motor car. As the number of ECUs increases, it inevitably results in more lines of software code to drive those systems.

3.5.1 Software bugs and errors

Automotive ECU software is often designed, developed and written by third party suppliers. However, according to Noergaard (2005), "guessing what the designer's intentions were most often results in more bugs". Studies into the quality of software indicate strong correlations between application size and the total number of defects (Ebert and Jones, 2009). Heiser (2007), states that a system consisting of millions of code lines could have tens of thousands of unknown or undetected bugs. The following figure highlights the increasing trend of vehicle recalls associated with software.

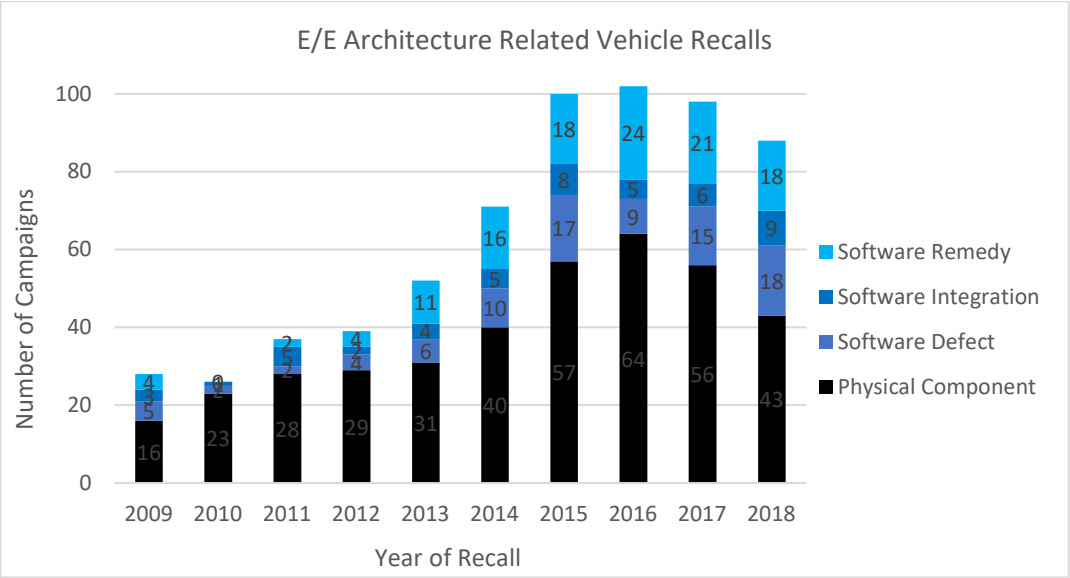


Figure 12: U.S. vehicle recalls relating to electronic components (Steinkamp et al., 2019)

In 2018, 8 million vehicles in the U.S. were affected by some form of software defect. According to Steinkamp et al. (2019), automotive recalls can be classified into four groups, three of which relate to software:

- Integrated electronic components - Failure of a physical, electronic component.
- Software integration - Software interfacing failure between different automotive components or systems.
- Software defect - ECU software failure.
- Software remedy – Fault not solely attributed to software failure but was remedied utilising a software update/patch.

Bugs and software errors can have disastrous consequences depending on the software's application and how critical it is to operational safety (Sax et al., 2017). For example, in 1996, the Ariane 5 Flight 501 rocket disintegrated 40 seconds after launch due to an undiscovered software error within an arithmetic routine installed in the flight computer. The software bug led to the backup and primary systems crashing, which ultimately led to the rocket's failure (Lions, 1996). According to Lin et al. (2016), the second most common reason for a vehicle-related collision is attributed to automotive software bugs.

Embedded software bugs and errors also cause control flow errors which are a flawed execution of the program that can lead to actuator failure or a computer program hanging or crashing (Thati et al., 2019). To mitigate against these types of errors in dependable and safety-critical systems, expensive hardware-based countermeasures such as triple modular redundancy are required. This mitigation technique uses a majority voting system where, if one of the three systems fail, the system will continue regular operation. Many ECU systems within the modern motor car are safety-related or considered safety-critical. Any failure in an automotive safety-critical system can potentially endanger vehicle occupant safety.

3.5.1 Software associated security threats

Vehicles are no longer closed systems that require direct physical access to gain unauthorised entry to the car. Vehicle connectivity is gaining popularity as it offers vehicle occupants a mechanism to connect to the Internet. However, the potential to compromise vehicle security through connectivity to gain access to an internal vehicle system now has the potential to come from anywhere. Nevertheless, even though connectivity systems have been incorporated into vehicles over the last few years, “car hacking” has not been widespread due to the limited potential for cybercrime and cybercriminals.

In 2015, two security professionals, Charlie Miller and Chris Valasaek, demonstrated how to remotely compromise a motor vehicle through its connectivity system and security vulnerabilities within its software code. They gained access through the HMI unit known as the Uconnect system in the Gran Jeep Cherokee target vehicle. This system incorporates an interface for particular vehicle operational and media functions. Due to vulnerabilities in the HMI operating system software, the software update validation mechanism was disabled, which permitted malware injection into the Uconnect software. Access to the CANbus vehicle network was possible through the design of this device. Once compromised, the system enabled the attackers to remotely inject spoofed CAN frames to ECUs which were responsible for vehicle control. The HMI vulnerability allowed the hackers to interfere with various vehicle subsystems, including interior climate control and vehicle windscreen wipers. They also manipulated safety-critical systems, including shutting down the engine and limited steering control. The Uconnect HMI is a standard product supplied by Fiat Chrysler and incorporated into numerous vehicle models across several different vehicle makes.

This software vulnerability could affect 100,000s of vehicles globally (Miller and Valasaek, 2015; Woo et al., 2016; Coppola and Morisio, 2016; Automotive IQ, 2017).

There is an emerging threat of vehicle cyber intrusion and manipulation with the increased frequency of autonomous features incorporated into the latest vehicle models. As the connected car becomes mainstream, it will ultimately become more of a cyber-criminal target (Boucherat, 2016). Vehicle autonomy and many current ADAS features place the vehicle in level 3 or 4 on the autonomy scale, where level 0 reflects complete driver control and level 5 reflects complete computer control. With these new autonomous driving functions becoming mainstream, an intruder's potential to gain remote system access and subsequent unauthorised control of a moving vehicle is an increasing possibility (Howden et al., 2020). Vehicle infotainment systems present a large attack surface that often delivers bi-directional vehicular connectivity. As such, any discovered vulnerabilities in this system software must be patched promptly to maintain the integrity of the vehicle's subsystems and occupants' safety (Happel and Ebert, 2015; Alam, 2016).

3.5.2 Ageing and out of date code

Automotive E/E components, including ECU hardware and associated software, is often designed and developed years before a particular vehicle model eventually leaves the showroom. The average vehicle has a life expectancy of between 10 to 15 years, and automotive software must mirror this long-time frame, as illustrated in the figure below.

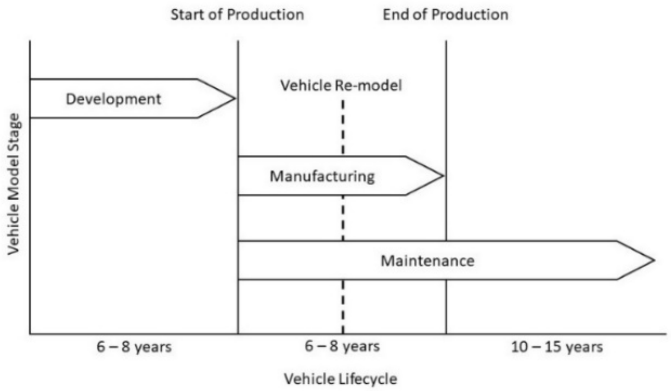


Figure 13: Vehicle lifecycle

Automotive system longevity significantly differs from many other software-based systems used in our day to day lives. For example, periodic software updates are routinely applied to our general-purpose computing and personal smart devices throughout their lifetime. Regular updates address flaws and bugs in software code, provide security and deliver new or additional system functionality (Chowdhury et al., 2018; Quain, 2018). According to Parnas (1994), software can exhibit signs of ageing where old software versions lose market share and customers to new software products. Furthermore, reliability can decrease because of the introduction of bugs and errors during periodic maintenance.

3.5.3 Aftermarket sales and additional functionality

Throughout its life, the modern motor car requires a robust aftermarket industry to sustain vehicle longevity. Currently, the automotive aftermarket sector is predominately concerned with two main revenue streams; services and parts. The service sector includes the maintenance and repair of vehicles, and accounts for approximately 45% of total European aftermarket revenue. The remaining 55% involves the sale of vehicle parts. The global aftermarket industry in 2015 was worth an approximate $760bn and accounted for 20% of total automobile revenues (Breitschwerdt et al., 2017).

It is generally recognised that individual or personal car ownership is declining due to several factors (Strauss, 2019).

- The rise of ride-hailing and car-share services, including UBER and Lyft, are gaining popularity with the general public, with revenues expected to grow to $218bn by 2025 (Curley, 2019).
- It is becoming more expensive to own a car. The motor vehicle is a high polluter and accounts for 7% of global CO_2 emissions (Hannappel, 2017). From 2021, manufacturers will face EU sanctions and fines if their products break new stricter emission limits. For manufacturers to comply with these strict exhaust emission standards, approximately £1,000 of additional vehicle hardware will be required, increasing vehicle retail costs.
- Furthermore, international trade tariffs, fluctuating economic markets and global economies result in the rising cost of raw materials, leading to higher vehicle retail prices.

Figure 14 highlights the most significant influence over new car purchase decision where 10 means in-car technology has the most significant influence, and 1 refers to the car's performance as the predominant factor. In response to this trend, infotainment systems that offer an "Apple-like" experience are predicted to grow from 18 million units in 2015 to 50 million by 2025 (Breitschwerdt et al., 2016).

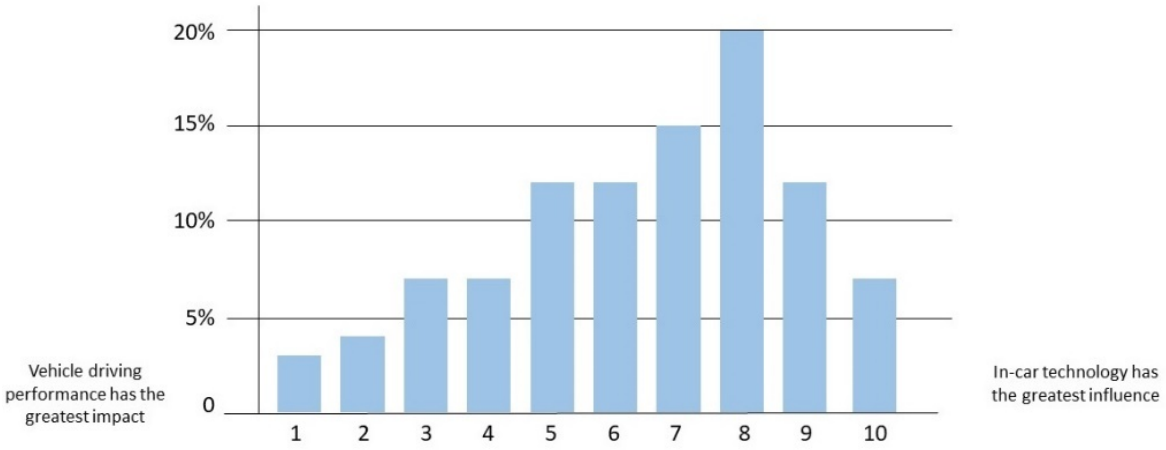


Figure 14: Consumer preferences in vehicle choice (Accenture, 2016)

Consumers are increasingly demanding the features and functions they use on their smart devices to be made available within their vehicles. The automotive industry is looking towards connectivity to provide the consumer with new automotive features and functions post-sale. Three of the six top trends surrounding aftermarket sales refer to new and emerging digital technologies, these include:

3.5.3.1 Interface digitisation

By 2035, there will be a predicted shift of between 20 - 30% from physical component replacement to software upgrades of vehicle components, including new digital services which can be purchased on demand (Breitschwerdt et al., 2017).

3.5.3.2 Car-generated data

Connected vehicles generate considerable amounts of telematics and driver data, approximately 25GB per hour. Through big data analytics, consumer-generated data can be of substantial value to the manufacturer in determining consumer insights, predictive maintenance and remote diagnostics.

3.5.3.3 The increasing influence of digital intermediaries

Usage-based companies and technology companies are increasingly utilising vehicle-generated data. These sectors will require mechanisms to facilitate the retrieval and frequent deployment of automotive software.

3.5.4 State of the art software

The automotive industry has attempted to address specific software-related concerns and issues. For example, AUTOSAR is a framework which can promote software reusability, but it does not address hardware re-use (Bo et al., 2010). MISRA – the Motor Industry Standards Reliability Association - is an automotive standard and guideline for the C programming language for developing embedded software products (MISRA, 2020). Founded in 2009, the principal goal of the GENIVI Alliance was ECU OS integration (GENIVI Alliance, 2020). However, there is still a heavy reliance on hardware, which is more challenging to re-use between vehicle models due to the rapid advancements in computing technology. Automotive Grade Linux (AGL) introduced in 2012 is an open-source project that aims to provide a Linux based reference framework to reduce complexity and development costs. However, this technology's target systems are intended for in-vehicle entertainment and telematics data, as such AGL has a limited application when compared with other ECUs within the automotive E/E architecture (Sivakumar et al., 2020). Lastly, vehicle longevity has led to inefficient practices and procedures in addressing how automotive software is patched and updated when a potential software related problem has been discovered.

3.6 Automotive Software Updating

In the modern motor car, almost all aspects of vehicle operation require considerable amounts of software code (Onuma et al., 2016; Petri, et al., 2016; Holmes, 2018). However, as with all software, automotive software needs to be periodically updated. In an increasingly software-centric automotive E/E architecture, new software installations may be required several times during a vehicle's lifetime. Any software update procedure must offer minimal disruption to the customer and be cost-effective to the manufacturer and

the supplier. There are several principle reasons why it is advantageous to update automotive software, these include:

- Addressing system failure through software errors and bugs.
- Patching or enhancing the system and software security.
- Adding value post-sale through aftermarket content.

Current automotive software update practices and procedures are problematic because there is no clearly defined mechanism or standard. Historically, when a common fault was discovered within a particular installed physical component of a vehicle, the Original Equipment Manufacturer (OEM) could issue a vehicle recall notice (Halder et al., 2020), especially if the fault concerned a severe safety issue.

3.6.1 Identified automotive update strategies

The current mechanisms for automotive software updates are ad hoc at best. This research has identified three mechanisms, including:

- Manufacturer-initiated vehicle recall process.
- Guided user intervention.
- Over the air update.

3.6.1.1 Software update mechanism: manufacturer-initiated recall process

Vehicle recalls are relatively common. For example, since 1966 in the U.S., over 390 million vehicles have been recalled due to safety issues (NHTSA, 2020). Like a physical component, a software-related problem, depending upon the severity, needs to be addressed and resolved. The recall mechanism, for both physical and software-related issues, requires the vehicle's return to a qualified engineer to rectify the problem (Sax et al., 2017). Vehicle recalls are an expensive exercise for the manufacturer (Lonn and Freund, 2009; Drolia et al., 2011; Sax et al., 2017). They are also a disruptive and time-consuming procedure for the customer (Hesham and Gansesan, 2014; Mckenna, 2016). The lengthy process of an OEM initiated software recall is outlined by Shavit et al. (2007), as outlined below, and as summarised in the subsequent figure.

1. Fault discovered in software.
2. Supplier / OEM tasked to provide a new updated software version.
3. The supplier provides OEM with new updated software version.
4. OEM notifies dealers and vehicle owner of a recall notice.
5. Vehicle owner takes the vehicle to a dealer.
6. Vehicle technician connects the vehicle to diagnostic hardware.
7. Technician updates and tests new software update.
8. Vehicle owner collects repaired vehicle from dealer.

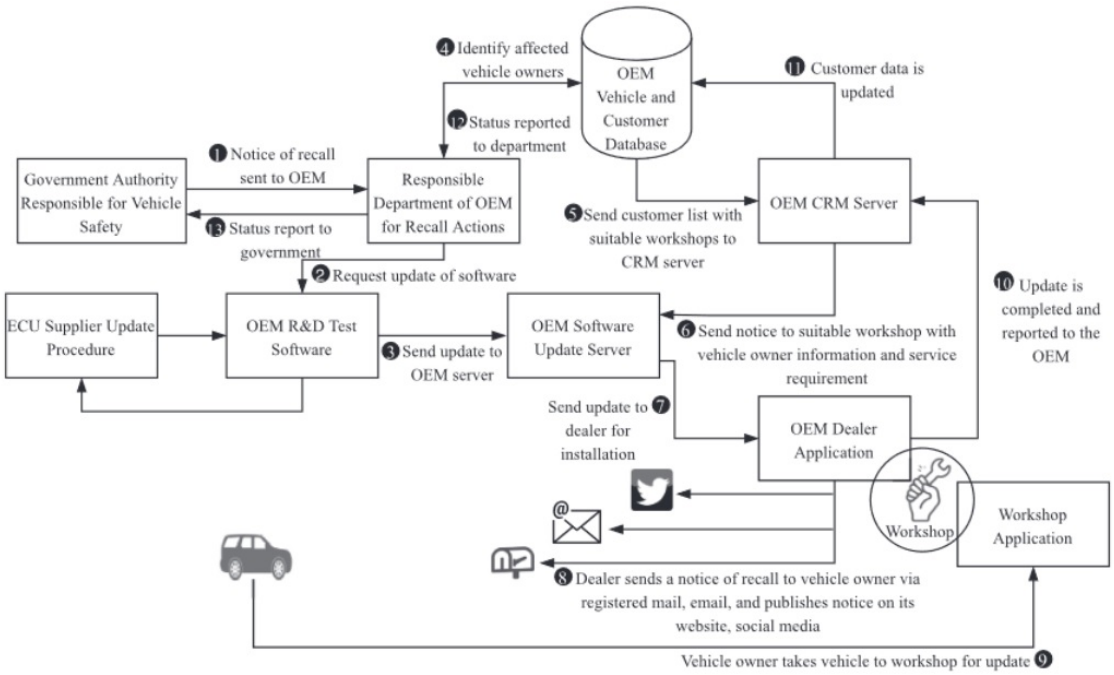


Figure 15: Example of a current safety recall procedure (Halder et al., 2020)

The process of a physical component fix may differ from a software fix. Physical components are replaced with new ones, often because of mechanical wear or a fault in the original component design or construction. In contrast, a software fault may require specialist equipment and a new software version installed on the existing hardware. However, this is not always possible with older embedded systems. Legacy ECU systems have their code pre-set at component manufacture. According to Broy (2006), high hardware optimisation often results in ECUs with minimal resources where limited storage, memory and processing capacity cannot accommodate additional lines of new software code. Limitations in ECU hardware resources require a similar exchange of hardware to repair a software-related fault. As such, like a physical component, ECU hardware exchange may be the only option to repair a software-related defect. This has led to a state where more than 50% of error-free hardware is replaced with entirely new hardware to resolve a software-related issue.

Incurred manufacturer maintenance costs can be high if a previously undetected software error or design flaw requires a vehicle recall (Kopetz, 2011). A much higher cost multiplier to repair a software fault post-production is applied when compared with identifying the same fault much earlier in the software development life cycle. Figure 16 highlights the cost multipliers associated with the different stages of the software development lifecycle (SDLC).

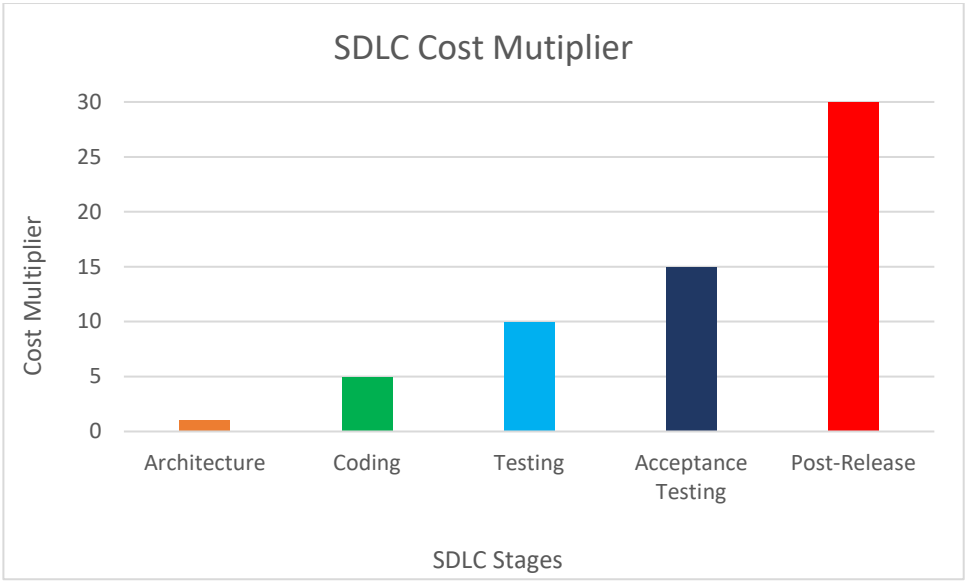


Figure 16: Cost multiplier of fixing a flaw at different stages of the SDLC

Cost is not the only factor in this update process. Customer confidence and brand loyalty can also be affected by software bugs and errors (Riggs et al., 2018). In recent years this has been an issue with the highly publicised Grand Jeep Cherokee cyber-attack (Miller and Valasaek, 2015; Coppola and Morisio, 2016; Automotive IQ, 2017).

3.6.1.2 Software update mechanism: guided user intervention

This mechanism utilises a physical input port installed inside the vehicle. Many modern cars provide a physical connection port for their owners' portable electronic devices, such as external Global Positioning System (GPS) and personal mobile devices, including MP3 players, mobile phones and tablets. These devices are often connected to the vehicle via a universal serial bus (USB) port. Using this port, vehicle owners are able to undertake their own software update either by inserting a supplied preloaded removable storage device or downloading a specific update from the manufacturer onto a USB device. Notably, Fiat Chrysler employed this type of update following the 2015 Grand Jeep Cherokee remote cyber-attack. Using the postal system, Fiat Chrysler distributed preloaded USB memory sticks with updated software to 1.4 million affected customers (Automotive IQ, 2017).

However, there are problems associated with this type of update mechanism. These include the following:

- Limited port functionality.
- Inaccessible code.
- Basic understanding of ICT.
- Willingness to undertake the task.

If any of the above prerequisites cannot be achieved, the software update will not be completed and it will be left unresolved. This software update method relies heavily on the customer having a particular level of technical knowledge and a willingness to perform the update process themselves. For example, there may be a reluctance to complete a necessary software update task due to a fear that their actions could "break the car", rendering it unserviceable and them responsible for any additional costs. This was observed by Fiat Chrysler during their guided user intervention update - many of the vehicles were not updated, prompting a vehicle recall. Furthermore, there are inherent security risks. This method is open to potential

exploitation from malicious threat actors that could enable unauthorised vehicle system access or the introduction of malware into the vehicle through compromised storage devices or software download files (Checkoway et al., 2011).

3.6.1.3 Software update mechanism: over the air (OtA) update

OtA mechanisms can update automotive software without the need to return the vehicle to an authorised garage or dealership, or relying on the customer to update themselves. Utilising on-board vehicle connectivity, OtA updates can deliver new software as and when required (Rouse, 2018). There are several options which can provide OtA software updates:

- Dedicated Short-Range Communication (DSRC) - is an 803.11p based wireless communication technology utilised for vehicle to infrastructure (V2I) and vehicle to vehicle (V2V) communication to aid and support ADAS and autonomous driving technologies. This communication technology can be utilised to transfer software updates between fixed infrastructure or vehicles (Guo and Balon, 2006; Vegni et al., 2013; Patterson, 2017). However, the primary issue with DSRC and automotive software updates is the relatively short time frames involved in V2I and V2V, especially when vehicles are travelling in the opposite direction.
- Cellular networks - in contrast to DSRC, cellular network technology (3G, 4G and 5G) can provide a stable high bandwidth communication mechanism. Software updates are downloaded by connecting to a particular cell tower within range, regardless of vehicle speed and travel direction. However, coverage may be restricted due to geographical limitations. Nevertheless, by utilising the extensive scope of cellular networks, future automotive software updates can be transmitted and downloaded to the target vehicle regardless of that vehicle's location. New software, when released, can also be downloaded.
- Fixed location Wireless Local Area Network (WLAN) - is another potential option for receiving software downloads. Updates can be sent to the target vehicle whilst parked, for example, at home or at work. Tesla has been utilising this OtA update mechanism from 2017 by using P2P wireless connections to download software from Tesla servers to target vehicles (Stegar et al., 2017).

Whichever form of OtA update mechanism is chosen, requires a vehicle connectivity solution. There are three modes of connectivity operation, depending upon the connection hardware type employed in the vehicle:

- Mirrored – applications stored on a paired portable smart device are replicated onto the vehicle's HMI unit. The application processing is usually performed on the smart device with screen updates sent to the HMI via a physical or wireless connection (Coppola and Morisio, 2016).
- Tethered – this type of connection utilises the paired device's communication technology. Applications are installed to the vehicle's HMI unit and application data processing is performed within the car.
- Embedded – a vehicle with this type of connectivity does not rely on a paired smart device but utilises its own connectivity hardware and installed applications.

There has been a widespread introduction of Long-Term Evolution (LTE) technology within the motor vehicle utilising one of the three aforementioned connectivity types in recent years. In fact, since 2019, this technology is estimated to be available in more than half of all new cars as can be observed in Figure 17 below.

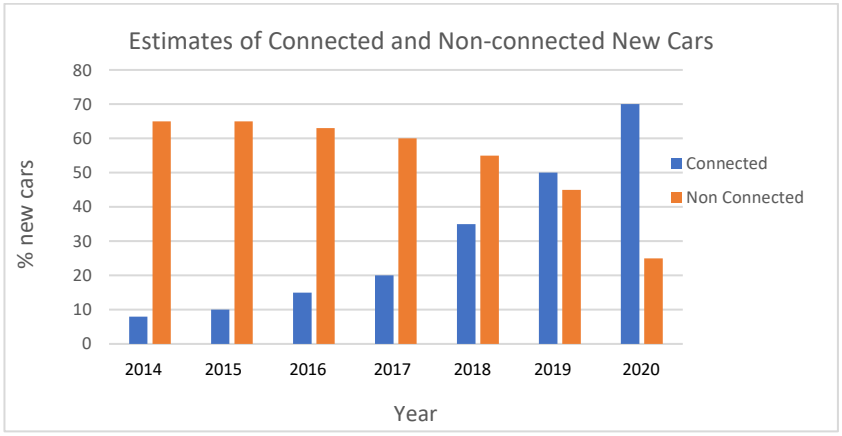


Figure 17: Estimated connected vs non-connected new vehicles (Coppola and Morisio, 2016)

3.6.2 The significance of OtA software updates

There are several benefits associated with OtA software updates, making it a promising technology for the automotive industry. This research has identified the following benefits:

- Reduction in vehicle recalls and associated costs.
- Vehicles can be updated in locations other than a dealership or maintenance garage.
- Centralised software – software updates can be distributed directly to the target vehicles without distributing to dealers and maintenance garages.
- Time to market – new software can be distributed as and when required rather than waiting for the customer to return the vehicle or waiting for periodic maintenance schedule.
- Convenience –updates can be performed at the customer's desired location and discretion, reducing vehicle downtime.
- Mandatory updates – new and updated software, especially where safety is concerned, can be pushed to the target vehicle without waiting for customer participation.
- Increase in safety – OtA software updates can reduce the time a vehicle is operated under faulty conditions.
- Proven technology – OtA updates are widespread in the telecommunication industry, which has provided users with new updated software via OtA mechanisms.

Gissler (2016) predicted that vehicle connectivity could be in all new motor vehicles by 2025. In 2015, Braun et al. (2015) suggested OtA software updates were an attractive technology for the OEM and the customer, with cost savings expected to reach $35 billion by 2022.

3.7 Chapter Summary

This chapter has focused on how the rise in the number of ECUs deployed into the modern motor car has increased overall automotive E/E architecture complexity. Decentralisation, as well as hardware and software optimisation, has increased further this complexity. However, complexity is not the only concern regarding the modern motor car and the automotive E/E architecture. There is no doubt that ECUs have had a positive impact on the motor car through the years, but there are many associated issues regarding its increasing use, relating to ECU hardware and software. As the number of ECUs rise, system costs increase – for components as well as development. Weight and power consumption relating to hardware are also contributing factors to cost.

In contrast to automotive hardware, automotive software contains several critical issues including how software bugs, errors and potential vulnerabilities are addressed and resolved. This chapter has also discussed changing attitudes towards new car purchases and the increased demand for post-sale functionality. However, inflexible ECU design has constrained resource capacity, which does not easily promote additional software-based functionality at a later stage. This chapter has investigated three software update mechanisms and how the automotive industry, in general, has applied these to resolving software related problems. The following chapter explores the benefits of virtualisation in addressing the identified complexities and software and hardware related issues, as highlighted in this chapter.

Chapter 4 Automotive Virtualisation

Objectives

- Provide an overview of virtualisation technology.
- Identify the different types of virtualisation.
- Investigate the benefits of virtualisation within the Automotive E/E Architecture.
- How virtualisation can address the identified automotive challenges and complexity.
- Future automotive E/E architectures utilising container-based virtualisation.

4.1 Introduction

Chapter 3 highlighted the complexities and issues concerning the increasing use and reliance on ECU hardware and related software. This chapter proposes using specific virtualisation technology to address the challenges facing the automotive E/E architecture. Over recent years, virtualisation technology has been employed by datacenters. This has led to considerably lower implementation and operational costs, specifically through server consolidation and a reduction in overall architectural complexity. Many of the benefits experienced by datacentre virtualisation can be realised within the automotive E/E architecture. This chapter puts forward and develops the main concepts, advantages and weaknesses of virtualisation technologies and how they can be applied within the modern motor car.

4.2 Overview of Virtualisation Technology

Virtualisation is not a new concept or technology and dates back to the 1960s. It was developed to divide system resources into separate and isolated entities to promote efficiency in large, expensive mainframe systems. Full system virtualisation refers to creating a virtual version of a physical computing system and necessitates three basic fundamental requirements:

- Equivalence – a program running on a hypervisor should behave identically to a program running directly within the OS and its underlying hardware.
- Resource control – the hypervisor must be in complete control of any virtualised resources.
- Efficiency – a portion of the overall machine instructions must be executed without hypervisor involvement.

Within full system virtualisation, there are two distinct variants – Type 1 and Type 2. Type 1 virtualisation runs directly on the underlying system hardware without the need for a host OS. The hypervisor or VMM operates in kernel mode, enabling direct access to the underlying system hardware (Aguiar and Hessel, 2010). These hypervisors are secure as they reduce the overall attack surface by removing a host OS requirement, which may have inherent security flaws and vulnerabilities (Plauth et al., 2017). In contrast, hosted Type 2 virtualisation is an installed software program within the host OS. Type 2 virtualisation VMs run as a process within the host OS (Popek and Goldberg, 1974). Any hardware access between upper-level

software and the underlying hardware has an increased latency level as resource requests must be scheduled through the VMM and the host OS. A guest OS executes within a VM, which emulates the host system including virtual BIOS, memory and associated system devices. The OS is not aware that the resources available to it are a virtual representation. In either instance, multiple different OSes can be installed on the same host within a VM and independent of other VMs. Figure 18 is a representation of the two types of full system virtualisation technologies.

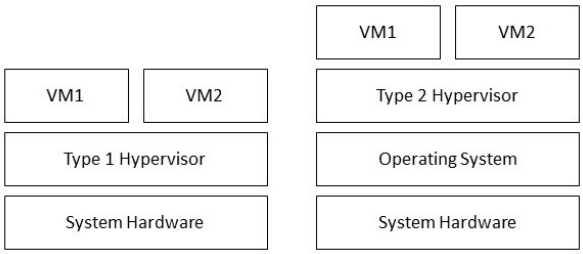


Figure 18: Type 1 and Type 2 full system virtualisation

4.2.1 Embedded hypervisor virtualisation

Embedded systems were initially simple functioning devices designed for a single purpose with rudimentary or no user interface. Modern embedded systems are very different in comparison. Mobile phone technology incorporates a sophisticated user interface with numerous mechanisms to select, interact and input data. Mobile phone technology incorporates a broad and varied range of base functions, including a high-resolution display, sound, voice and data communication, and application features. Specific embedded system hypervisor requirements include:

- Small footprint – ideally suited to the hardware resource constraints within mobile phone architectures.
- Real-time capability.
- Temporal and spatial isolation.
- Processor support – mobile phones utilise different processor types ideally suited for embedded systems from standard desktop and server computing platforms, where support for specific processors is required.

The mobile phone industry has significantly driven the development of embedded system virtualisation, supported by capable hardware resources including 64-bit multi-core processors operating in the 2 – 3 GHz range and system memory ranging in the GB range. The Apple iPhone 11, for example, includes 4GB of system RAM and a 64-bit 2.65GHz Advanced RISC Machine (ARM)-based processor offering 18 CPU cores, six-core CPU, four-core GPU and an eight-core Neural Engine processor supporting machine learning processes (Surana et al., 2020).

The automotive embedded system, however, is very different to mobile phone design. Modern automotive ECU design lacks some of the fundamental technologies to support a hypervisor environment. Automotive embedded system microcontroller design lacks support for hypervisor memory management and CPU privilege mode limitations required for hypervisor system hardware access. There have been various unique approaches to automotive embedded hypervisor design. For example, the ETAS RTA Lightweight Hypervisor utilises a multicore based ECU where one core known as the master core runs its OS and the lightweight hypervisor (Dasari et al., 2020). Figure 19 shows the ETAS RTA hypervisor architecture. The other CPU cores known as application cores are responsible for executing VMs (Reinhardt and Morgan, 2014; Hauser et al., 2017).

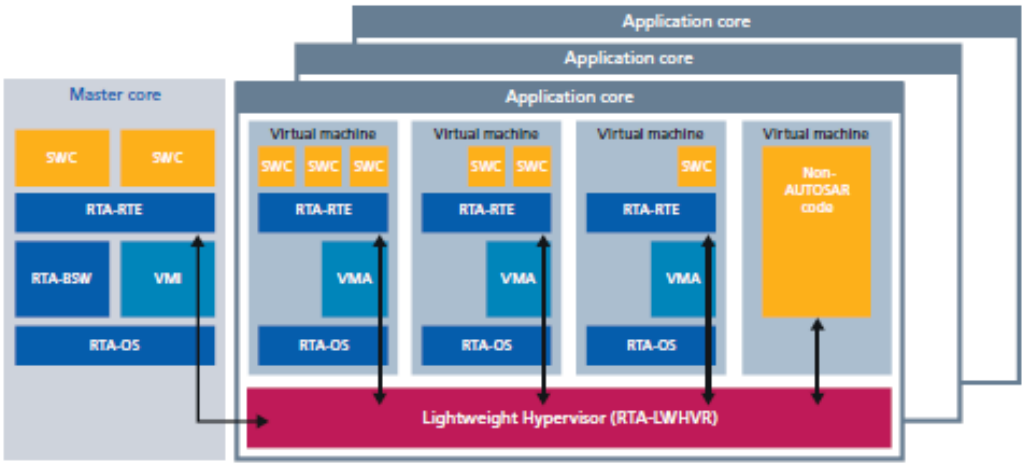


Figure 19: ETAS RTA embedded hypervisor (Hauser et al., 2017)

In contrast to full system virtualisation and custom embedded hypervisors, operating system-level virtualisation, which was introduced in the 1980s, addresses many of the identified automotive E/E architectural issues and complexities.

4.2.2 Operating system virtualisation or containerisation

OS virtualisation represents a newer virtualisation technology. This virtualisation technique, also known as containers or containerisation, differs from conventional hosted and bare-metal virtualisation technologies. Figure 20 shows a basic application container architecture.

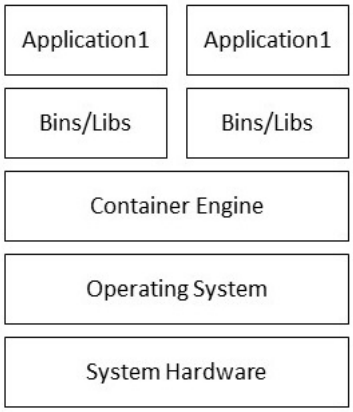


Figure 20: Container architecture

OS virtual memory is segregated into two different entities; kernel and userspace:

- Kernel space is reserved for running privileged kernel extensions, running processes and managing hardware. It is the heart of any OS and is responsible for all system hardware and software interactions.
- Userspace primarily executes application software and low-level system components.

Kernel and userspace segregation prevent userspace program data from interacting with kernel space data. Only the specific binaries, libraries and host system resources required to run a particular application are included during container creation.

4.2.3 Major container components

Each container is comprised of the following components:

- Container daemon – image build and management, authentication and security.
- *containerd* – manages the container lifecycle operations (starts, stops, pause).
- *runc* – single purpose, small, lightweight Command Line Interface (CLI) wrapper/container daemonless runtime tool.
- *shim* – the shim process becomes the containers parent process, controls the running container.

4.2.4 Container creation process

Each particular container is specific to the image it was created from. The process of starting a container is:

1. Container client contacts the container daemon.
2. Container daemon pulls image from repository if image does not exist.
3. Container daemon creates new container from image.
4. Container client converts container CLI commands into an appropriate Application Programming Interface (API).
5. API is implemented in the container daemon which calls the *containerd* to begin the container creation process.
6. *containerd* invokes *runc* which interfaces with the OS kernel to construct the container ecosystem with the necessary components.
7. Container process is started as a child process of *runc.*
8. Once created, the *runc* process exits and the container *shim* assumes parental control of the newly created container.

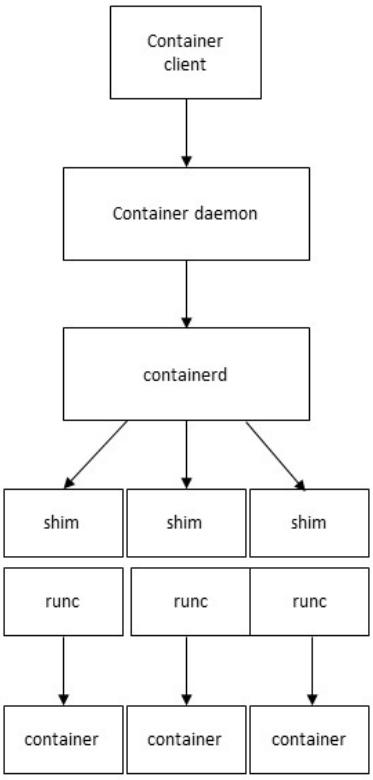


Figure 21: Container creation cycle

4.3 The General Benefits of Virtualisation within the Automotive E/E Architecture

Virtualisation has seen some significant returns within client/server architectures, data storage and cloud computing environments, especially in hardware consolidation and overall cost reduction. These benefits include reducing infrastructure costs and hardware expenditure, higher system redundancy levels, and increased productivity and security through strong levels of isolation. Similarly, virtualisation technology within the automotive E/E architecture can address many of the concerns mentioned earlier in chapter 3. However, virtualisation technology has not been rigorously studied within the automotive domain other than the vehicle HMI device (Gaska et al., 2010; Reinhardt and Kucera, 2013).

4.3.1 How virtualisation can address hardware related issues

Consolidation through virtualisation has played a large part in reducing individual bespoke servers within the datacentre, bringing them into a centralised, manageable location. Strobl et al. (2013) propose the concept of "hardware obliteration", where physical hardware is replaced by software (i.e. VM). Automotive E/E architecture enables ECU consolidation, which can be achieved in conjunction with virtualisation technology, where numerous individual hardware-based systems can be consolidated onto a single platform, thus promoting operational efficiency and a reduction in overall complexity and running costs. Dedicating multiple ECU instances onto a single system addresses many of the issues described in chapter 3. These include:

- Load balancing – hardware resources from other hosts can address peak system demands where additional VMs are created on-demand on underutilised hosts. Before exceeding a specifically defined threshold, on-demand VM creation can balance the overall system load across several available computing platforms.
- Weight savings - the consolidation of individual ECUs reduces overall system weight. Grouping similar functions onto single systems also reduces the requirement for inter ECU data transmission via an in-vehicle network solution. Virtual ECU instances can communicate via virtual internal networks, reducing network infrastructure and overall associated weight.

- Power consumption – energy conservation is a crucial problem within modern automotive E/E architectures. Powering down dormant ECUs to save energy use through ECU shut down or hardware sleep techniques is a concept that has been researched in several publications over the years (Heiser, 2008; Navet and Simonot-Lion, 2009; Vegni et al., 2013). Underutilised computing platforms can migrate active virtual instances to other hosts to power down redundant hardware (Strobl et al., 2013).

4.3.2 Virtualisation addressing system security through isolation

Virtualisation offers isolation, which addresses two primary concerns - overall system security and corruption propagation (Heiser, 2009; Compagna and Violante, 2012). Virtualisation provides a clear separation of services whereby specific applications, processes and functions can be separated across individual VMs. If a service within a particular VM is compromised for any reason, it will not directly affect the integrity or security of other VMs within the same system. Figure 22 shows a potential attack on a VM through its user interface, but this attack does not enable access to the different VMs hosted on the same hypervisor/system.

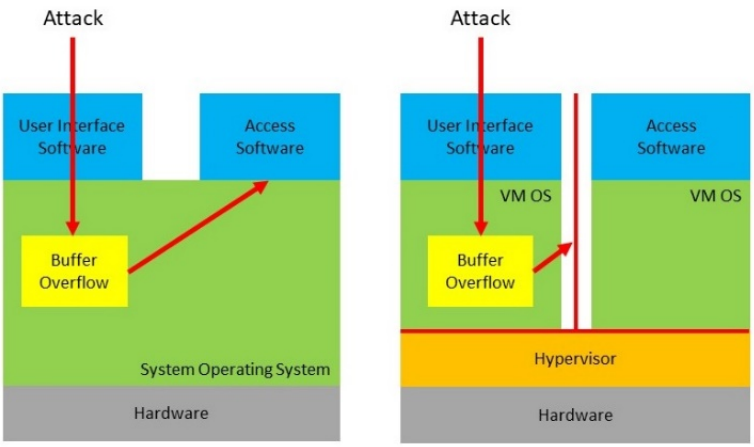


Figure 22: Isolation from attack propagation (Heiser, 2007)

4.3.3 How virtualisation can address automotive software related issues

Chapter 3 highlighted many areas of concern relating to ECU hardware as well as its related software. As mentioned previously, virtualisation has several hardware benefits but it also addresses numerous software related concerns including security, bugs and errors, and how to address out of date code and aftermarket sales. In particular, periodic software updates are easy to perform because they use a virtual presence rather than a fixed hardware-based system, and are often much more accessible and cost-effective to update and replace than hardware. Heiser (2009), stated that firmware OtA software updates could be achieved through virtualisation where a hypervisor can reduce the amount of infrastructure required to support new updated software, which is a limitation in fixed ECU hardware.

4.4 Future automotive E/E architectures utilising container-based virtualisation

There are some fundamental issues concerning the incorporation of full system virtualisation into an ECU based automotive E/E architecture. There is no doubt that virtualisation is an ideal solution for system consolidation because a single computing device hosts multiple services. Furthermore, consolidation through virtualisation promotes the reduction of complexity and increases diverseness and manageability. However, virtualisation heterogeneity comes at a cost when considering small scale embedded computing devices. Some of the benefits realised by full system virtualisation do not apply to many ECUs found within the automotive E/E architecture. Full system virtualisation or VMs create an emulated hardware platform within a software environment, which often require a full-size OS. Full system virtualisation usually incurs performance and memory disadvantages and an extensive software footprint depending on its implementation. The hypervisor or VMM layer increases context switching. This has a detrimental effect on I/O performance, which can be a critical factor in ECU functionality and often detrimental to an ECU based system (Felter et al., 2015).

OS virtualisation is a promising technology for automotive ECUs because it addresses some of the problems that arise from the use of full system virtualisation within the automotive E/E architecture whilst maximising the benefits that virtualisation can provide.

4.4.1 The container ecosystem

Containers utilise two crucial aspects of the Linux kernel: *cgroups* and namespaces.

- Control groups (*cgroups*) - control and limit how much system resources a process can access, as well as manage process prioritisation.
- Namespaces - isolate the process's view of the system, including the filesystem and network access.

Namespaces enable process isolation on the system level, whereas *cgroups* manage that process's resources – combined, they provide an effective virtualisation technique. Full system virtualisation utilises VMs that require an individual OS kernel and associated system resources to support services, applications and software in execution. In contrast, containers share the host OS kernel, binaries and libraries. Without the need to replicate these key OS components, this dramatically reduces individual container size, making them a lightweight virtualisation technology. A container is constructed from a sequence of layers held within an image. These image layers define container configuration and associated software, libraries and binaries required to run a program within the container.

4.4.2 Additional hardware benefits of containers within the automotive E/E architecture

As identified previously, there are a number of benefits associated with full system virtualisation. Container-based virtualisation can utilise these identified benefits, but can also realise additional specific hardware-based advantages, which include:

- Performance - the hypervisor layer can impact system performance. However, a container can perform at near-native speeds with little additional overhead required to run a containerised application. Therefore, containers are ideally suited to embedded devices where quick response times are vital to providing a safe system.
- Modularity and scalability - application functionality can be placed into a single container or divided and distributed across multiple containers. Individual components can be upgraded or updated independently if required.

- Heterogeneity - full system virtualisation requires large amounts of system resources to support their VMs. Multiple VMs often require extensive resource available servers. Large computing systems that support multiple VMs require more power and space, which is of limited supply within an automotive context. Containers have a diverse array of hardware types that they are suited too. Hardware architectures supporting container virtualisation are diverse, ranging from large enterprise servers often found in cloud and datacentres to small embedded systems.

4.4.3 Additional software benefits of containers within the automotive E/E architecture

Container-based virtualisation utilises several benefits associated with full system virtualisation but also realises additional specific software-based advantages, including:

- Isolation - containers have similar goals to VMs, namely application and dependency isolation. Isolation becomes more granular as specific services are isolated within individual containers, thus reducing the attack surface and increasing the trusted computing base.
- Lightweight - containers are quick to initialise. In comparison, VMs usually take longer whilst they go through the process of booting up their underlying OS. ECU functionality is often a small program or process running on a bespoke piece of hardware. These types of ECU are an ideal candidate for container virtualisation rather than full system virtualisation. Their lightweight architecture enables containers to be stopped and started within minimal time frames ranging in milliseconds. An application can be isolated within its container without a separate OS to host each application. A lightweight virtualisation approach results in multiple containers hosted on a single hardware platform. Sharing common libraries and binaries results in image and container footprints ranging in the megabyte range rather than the gigabyte range.
- Layered architecture – unlike a VM, where all its associated system and application software are confined into a single software image, containers are created using a layered image. Containers are constructed from a set of defined layers held within an image. Any subsequent change made to a particular image layer affects all new containers built from that altered image. Unlike a VM, a container image does not need to be replaced in its entirety. If an image layer is changed, only

that affected layer is downloaded and inserted into the existing image, similar to a delta/difference file software update. These container image layer changes reflect configuration settings, new or additional software, or particular changes to a software layer. Any changes within a layer will only affect a new container started from the original updated image.

- Continuous software integration - new software code can be integrated into a particular system with more frequency, which aids in more accurate and robust software code before being delivered to the target ECU.

4.5 Chapter Summary

To facilitate the addition of new ADAS and autonomous driving technologies, the requirement for more ECU computing power and vehicle subsystem digitisation will undoubtedly increase. A new architecture design is required to address the issues and complexities of the automotive E/E architecture. Whilst there are many benefits that can be applied to the automotive E/E architecture utilising virtualisation technology, this research has identified that full system virtualisation does not suit automotive ECU design requirements. For example, an OS and its applications executing within full virtualisation environments can be considerably slower than native non-virtualised systems. This is because any privileged access to memory or devices is initially trapped by the hypervisor, which then checks for availability before forwarding requests - this can add additional latency to overall system performance. In contrast, containers can operate at near-native speeds and offer similar advantages as full system virtualisation, providing other hardware and software benefits as highlighted above.

Chapter 5 Container System Prototype

Objectives

- Design of the container-based automotive system prototype testbed.
- Describe the implementation of the container-based automotive system testbed.
- Identify and design a suitable automotive function for testing container-based ECUs.

5.1 Container System Prototype Introduction

This research aims to establish a container-based virtualised ECU architecture to support automotive software functions and facilitate a structured software update mechanism. In order to test container suitability, a test environment is required that models a specific ECU-based automotive process. The literature reveals that automotive ECUs are specifically designed to undertake a particular vehicle task or function, where supporting hardware is often bespoke and associated software is highly optimised. High optimisation levels reduce costs, minimise system power use and promote speed of operation. However, to address identified problems surrounding the increasing use of bespoke ECU hardware, a more generic type of hardware is required to test the application of containers.

A crucial feature of any ECU based system is the microprocessor, which is usually an ARM processor (Wang & Yang, 2004). This type of microprocessor has a Reduced Instruction Set Computing (RISC) architecture, where every instruction within a process is broken down into small, simple steps executed during a single clock cycle. ARM processors are ideal for embedded systems such as ECUs because they have minimal power consumption rates yet high processing power. To replicate ECU hardware as closely as possible within a testbed system, a hardware platform that utilises an ARM processor architecture is required. As such, the proposed hardware test system comprises of multiple small generic ARM-based computing devices. This chapter examines the requirements of a vehicle door central locking mechanism hosted within a container-based ECU and presents the design and implementation of the required hardware and software incorporated within the automotive testbed.

5.2 Automotive Regulations

The automotive industry is heavily regulated regarding the design and implementation of computing systems deployed within the vehicle. To address the increasing use of safety-critical systems within the modern motor car and identify their potential risk of failure the motor industry, has, since its publication in 2011 begun to apply the international standard for automotive safety: ISO 26262. It is an adaptation of the non-automotive specific International Electrotechnical Commission IEC 61508 Programmable Electronic

Safety-related Systems standard (International Organization for Standardization, 2011). ISO 26262 applies to safety-related automotive E/E systems [hardware and software] and addresses the potential dangers from a safety-related systems failure (Smith and Simpson, 2016). The standard covers several significant topics to support the automotive industry, including providing guidelines for the automotive lifecycle incorporating management, development, production, operation, service and decommissioning.

To ensure and maintain high design specifications and safety within the ISO 26262 standard, each automotive E/E safety-critical system is assigned an ASIL. ASIL is an extension of the IEC 61508 Safety Integrity Level (SIL). ASIL levels are classified as:

- ASIL D – the most stringent level of safety (high risk).
- ASIL C.
- ASIL B.
- ASIL A – the least stringent level of safety (low risk).
- QM (Quality Management) non safety-related level.

An ASIL level comprises of the severity of injury, probability of exposure and controllability of the risk. An example of an ASIL D level would be systems that interact with the steering and braking of the vehicle, requiring the highest levels of safety during operation. For the purposes of this research, any automotive function and responsible subsystem selected as part of the modelled automotive process will fall within the ASIL A or QM level.

5.3 Control Systems and Control System Transactions

Almost every automotive ECU involves a control system. The fundamental process of a control system is to receive information from a physical process, perform a control function that produces an output which, in turn, affects a physical process. ECU software functions within a control system establish a Control System Transaction (CST) which is a series of software tasks:

(**P**)rocess → (**I**)nput → (**C**)ontrol Function → (**O**)utput → (**P**)rocess

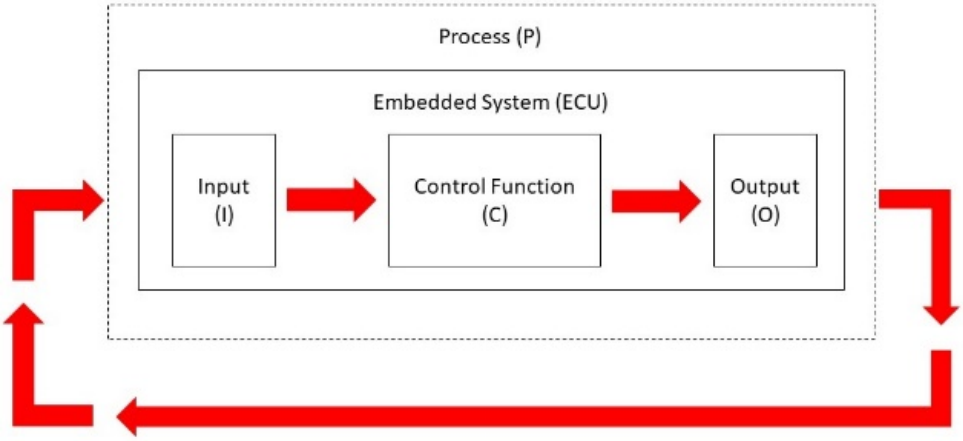


Figure 23: An example CST

Two distinct properties define CST: casual and timing.

- A casual property implies there is a cause-effect relationship where the output affects process (O → P).
- The timing relationship is where the control function happens before the output (C → O).

In Figure 23, the CST is an isolated example of a process which has its dedicated inputs and outputs that affect the initial procedure. More often than not, ECU functions are distributed across several sensors, actuators and additional ECUs, whereby the initial data is collected, processed and subsequently transmitted over a communication media to another control system. This will combine any process and distributed process inputs to produce an entirely different process output, as illustrated in Figure 24.

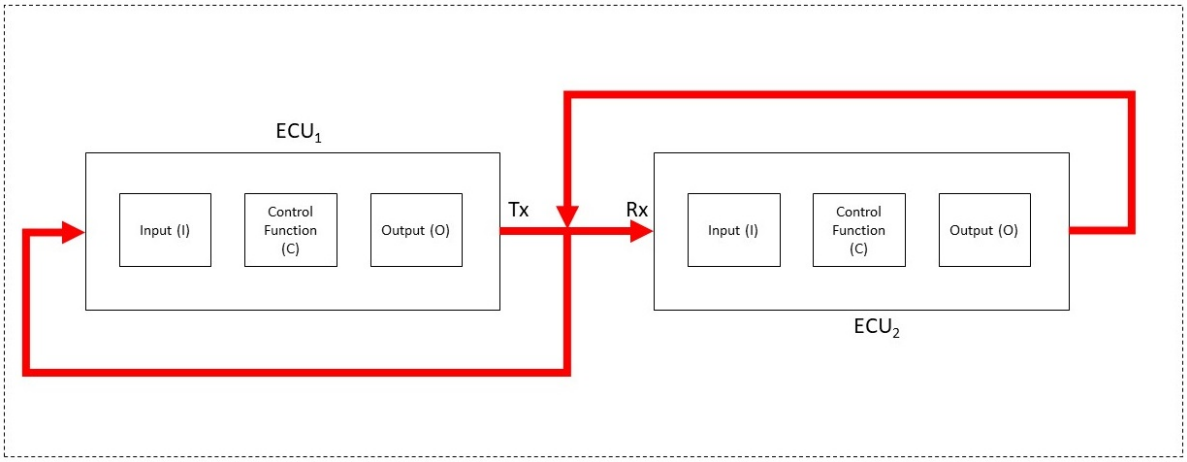


Figure 24: Example of a distributed software function across two ECUs

- ECU1 collects the data from its attached peripherals and passes this data to ECU2.
- ECU2 processes external and local data, and affects its own attached peripherals.

$$P \rightarrow I \rightarrow C \rightarrow O \rightarrow Tx \rightarrow Rx \rightarrow I \rightarrow C \rightarrow O \rightarrow P$$

This example is replicated throughout the automotive E/E architecture, which often utilises multiple ECUs and in-vehicle networking. The diagram in Figure 25 illustrates how several separate systems are activated when the reverse gear is selected. This seemingly simple vehicle function actually requires a total of eight ECUs with interacting CSTs. When the driver selects the reverse gear, the following actions and interactions take place:

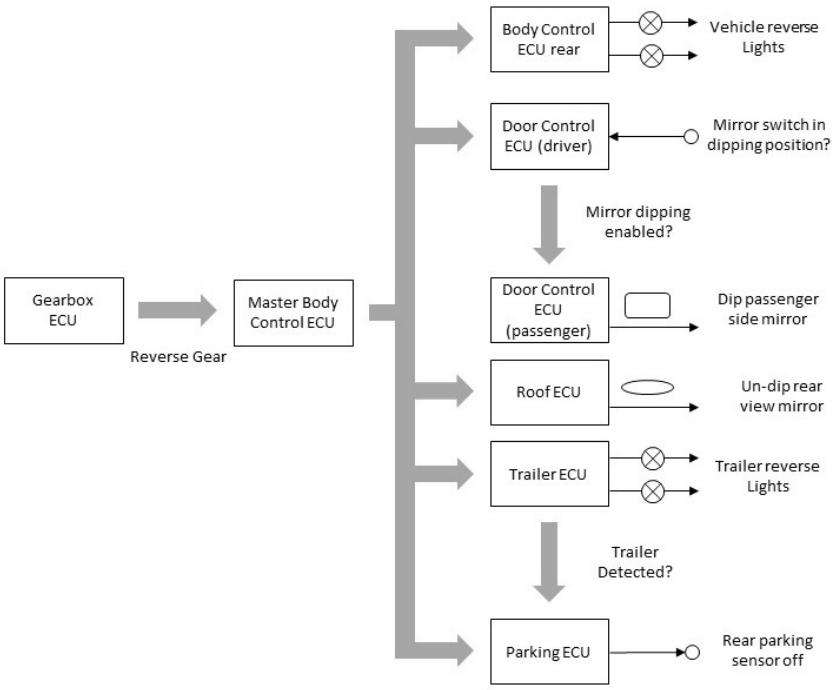


Figure 25: Audi reverse gear / light function

1. When the reverse gear is selected, the gearbox transmits data to the master body controller ECU.
2. The master body control module decides which subsystem ECU is required, depending upon the input received.
3. Information is transmitted to the body control ECU rear which activates the lights.

Although the process has accomplished the primary task of illuminating the reverse light, more dependencies are initiated as part of this function.

1. The same information passed to the body control ECU rear is used by the driver door control ECU to dip the passenger mirror via the passenger door control ECU.
2. The roof control ECU un-dips the rear-view mirror.
3. If an attached trailer is detected, the trailer ECU activates the trailer lights.
4. If an attached trailer is detected, the vehicle parking sensors are deactivated via the parking ECU.

This simple mechanism of activating the vehicle's reversing lights when the reverse gear is selected requires distributed domain data and communication between the transmission and the body control domains with numerous ECU interactions between various isolated body control ECUs. Hence, it is clear that to test a

container-based ECU system resource use and interaction, the modelled testbed will require a combination of isolated and distributed ECU control systems.

5.4 Automotive Central Locking Mechanism

One standard automotive process prevalent across most vehicle models is the door central locking mechanism. On first consideration, this vehicle function appears to be a simple mechanism that locks and unlocks selected doors using a remote key fob. However, there are many different types of vehicle door central locking mechanisms and associated trigger mechanisms across various vehicle makes and models. With more expensive models, more advanced system functionality is offered, including comfort functions such as specific driver seat and mirror adjustments depending upon how the vehicle is accessed. Figure 26 illustrates a typical central locking mechanism with 18 system interactions/trigger mechanisms (Cook, 2007).

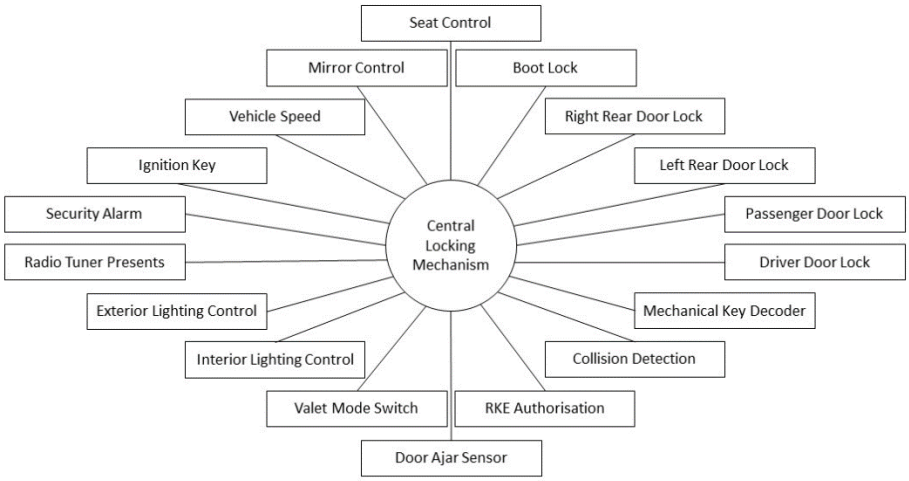


Figure 26: Central locking context diagram (Cook, 2007)

The locking mechanism can be triggered by vehicle speed. For instance, when the vehicle exceeds a minimum speed, the system activates and locks the doors (Broy et al., 2007). As more additional features are included in its basic operation mode, this primary vehicle function has become increasingly complex. A central locking system monitors the state of the door lock switches and any wireless input. Although it is also connected to safety-critical systems that disengage the door locks, such as when a collision is detected (Checkoway et al., 2011).

5.5 Automotive Central Locking Test System Model Requirements

A central locking mechanism incorporates distributed and isolated systems in conjunction with real and non-real time data. This type of automotive process is an ideal candidate to model and test within a container-based environment. To accurately model a “live” central locking mechanism, locking and unlocking selected vehicle doors is the primary system function. This primary function is supported by supplementary or sub-functions that trigger the mechanism and provide additional system functionality, across different automotive domains. Figure 27 details the functional architecture of a central locking mechanism.

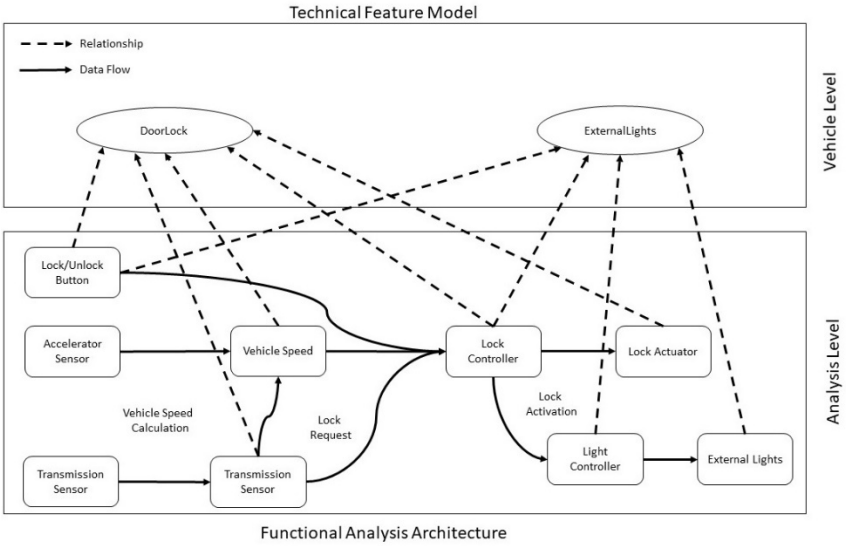


Figure 27: Central locking mechanism functional architecture

The identified triggers for the modelled central locking function are:

- User-initiated manual locking of all doors via a remote wireless Infrared (IR) device.
- User-initiated manual unlocking of all doors via a remote wireless IR device.
- User-initiated manual locking of a single (driver) door.
- User-initiated manual unlocking of a single (driver) door.
- Automatic locking of all doors on the selection of a specific gear.
- Automatic unlocking of all doors on the selection of a specific gear.

- Automatic locking of all doors when a specific vehicle speed is achieved.
- Automatic unlocking of all doors when a safety mechanism is activated.

To meet the basic system functionalities, the test model will include a basic lock/unlock functionality initiated by three individual triggers:

- IR remote.
- Gear selection.
- Vehicle speed.

The output of these triggers is the locking and unlocking of all vehicle doors or unlocking of the driver's door. Additional system functionality for the modelled central locking mechanism includes several visual and safety features. When a central locking mechanism triggers on many vehicle models, the vehicle's external lights flash. Flashing lights signal that the lock/unlock mechanism has initiated and acts as a vehicle locator. Safety is a primary consideration for vehicle egress. The modelled system will incorporate a mechanism where all vehicle doors automatically unlock upon detection of a collision via a safety sensor.

5.5.1 Central doorl lock/unlock primary functionality

The primary function of the modelled system is to alter the current door state to a new door state through specific trigger mechanisms. The vehicle doors can be in one of the following three states:

- All doors locked.
- All doors unlocked.
- Only driver's door unlocked.

A particular door state is triggered depending upon received data from several distributed vehicle subsystem processes, as outlined below.

5.5.2 Basic remote central locking door state selection

The vehicle doors can be locked and unlocked remotely. One of the three-door states are selected via a remote IR transmitter, these include:

- Lock all doors.
- Unlock all doors.
- Unlock driver door only.

The door lock mechanism activates via a remote IR device simulating a vehicle key fob. An IR receiver sensor reads the incoming signal sent via one of the selected keys on the remote IR device. The corresponding IR code is transmitted to the Door ECU which, depending on the signal received, activates one of the three-door states.

5.5.3 External vehicle lighting function

This auxiliary function activates in conjunction with the IR remote central locking/unlocking process. The Light ECU is responsible for the vehicle's headlight mode and operation, and often incorporates the function of the vehicle's direction indicators. In the context of this research, the lighting system has a simple process that simulates the flashing of the vehicle indicators when the vehicle doors are locked/unlocked. This feature is simulated using a Light Emitting Diode (LED) that flashes a specific number of times depending on door state selection via the remote vehicle key fob. This vehicle function will only activate when the vehicle is in a neutral transmission state. The lighting ECU will not trigger when the door mechanism is activated automatically via the collision sensor, gear selection or vehicle speed. The external lighting function activates when the IR receiver receives one of the three selectable door states.

- All doors locked → five light flashes.
- All doors unlocked → four light flashes.
- Drivers door unlocked → three light flashes.

5.5.4 Transmission activated, door lock/unlock function

This vehicle function is responsible for gear selection. There are six different gear states (neutral or first to fifth). Table 1 highlights the currently selected gear and corresponding door state.

Current Selected Gear	Central Locking/Unlocking Door State
Neutral Gear	Enables IR and external vehicle light related functionality Automatically unlocks all doors upon neutral gear section
First Gear	No change in door state
Second Gear	No change in door state unless vehicle speed exceeds 50km/h
Third Gear	Automatically locks all doors
Fourth Gear	Automatically locks all doors (if previous gear skipped)
Fifth Gear	Automatically locks all doors (if previous gear skipped)

Table 1: Transmission activated door lock/unlock function by selected gear

5.5.5 Vehicle speed activated, door lock/unlock function

This vehicle function relates to the position of the vehicle accelerator pedal. To determine the simulated vehicle speed requires information pertaining to the accelerator pedal position and the current selected gear. The accelerator pedal position equates to engine acceleration, which ranges from 0 – 6000 r/min. The r/min range simulates a standard range of engine revolutions during a motor vehicle's driving operation. The accelerator sensor provides the Engine ECU with a constant stream of real-time data relating to the simulated accelerator pedal position. This stream of real-time data is converted from analogue output to a digital data stream and is subsequently sent to the Engine ECU where the ECU software processes the data. The combined selected gear and engine r/min produce a corresponding simulated vehicle speed range, as observed in Table 2.

Vehicle Speed	Current Gear	Central Locking/unlocking Door State
N/A	Neutral Gear	No change in system state
0 – 20km/h	First Gear	No change in system state
21 – 50km/h	Second Gear	No change in system state unless speed equals 50km/h
51 – 80km/h	Third Gear	No change in system state unless speed exceeds 50km/h
81 – 110km/h	Fourth Gear	No change in system state
111 – 160km/h	Fifth Gear	No change in system state

Table 2: Vehicle speed activated door lock/unlock function

5.5.6 Safety/collision sensor

This safety function overrides any current door state if a collision is detected.

- Collision detected → Unlock all doors if they are not already in an all unlock state.
- No collision detected → No change in system state.

The collision sensor is physically connected via the Door ECU General Purpose Input/Output (GPIO) pins - when this sensor is activated, the “all doors unlock” function is activated. This safety function simulates an automated collision detection function triggered via a dedicated impact detection sensor or vehicle airbag deployment. This trigger mechanism overrides all other unlocking functionality (gear selection or vehicle speed) and automatically unlocks all of the vehicle doors to allow for quick egress in the event of an emergency.

5.5.7 Testbed system design

A modern vehicle door central locking function is triggered through a series of isolated and distributed CSTs (Broy et al., 2007; Cook, 2007; Pretschner et al., 2007; Koscher et al., 2010). Figure 28 details the central locking mechanism and its subsidiary functions developed for this research.

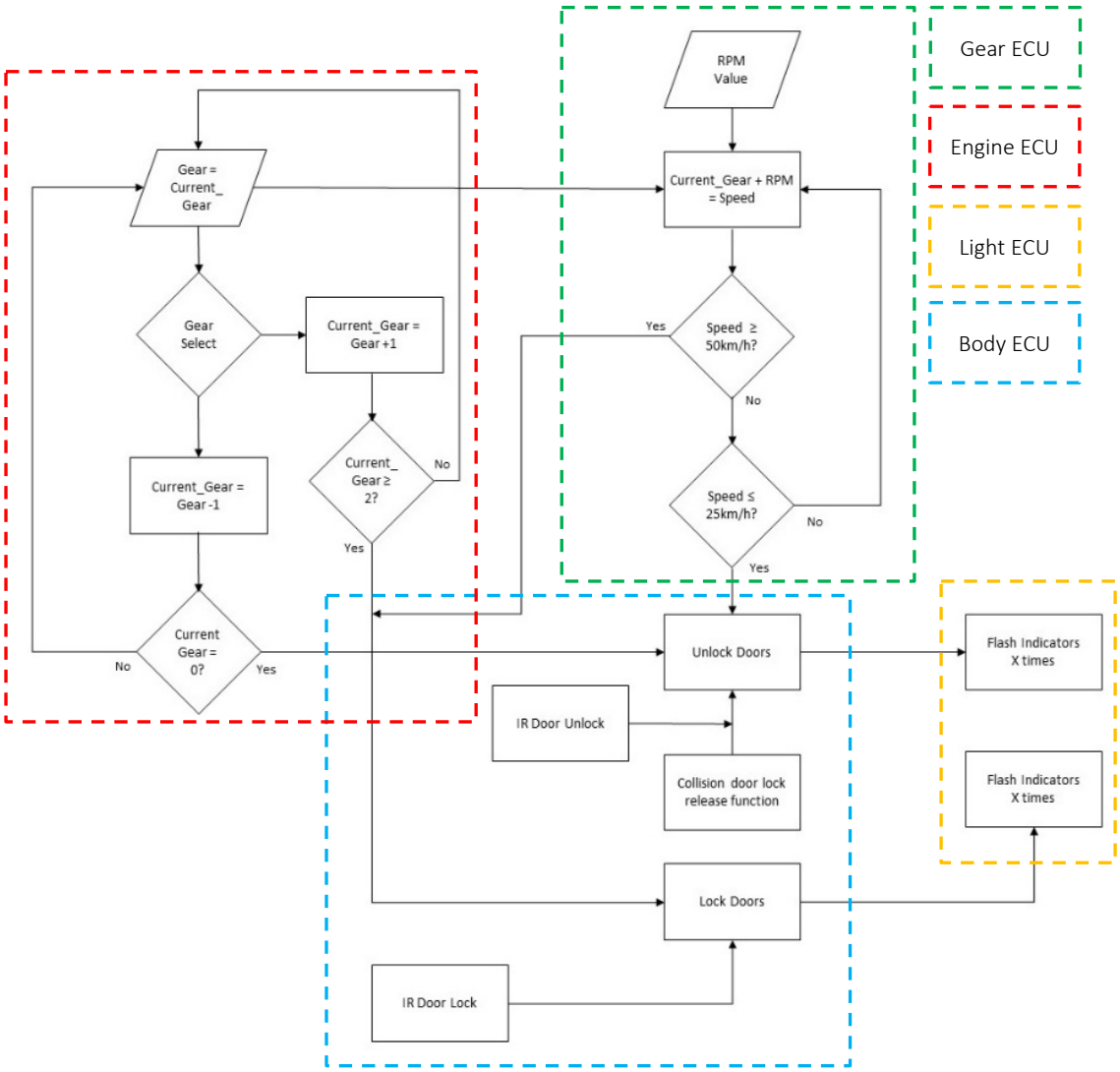


Figure 28: Central locking function process flowchart

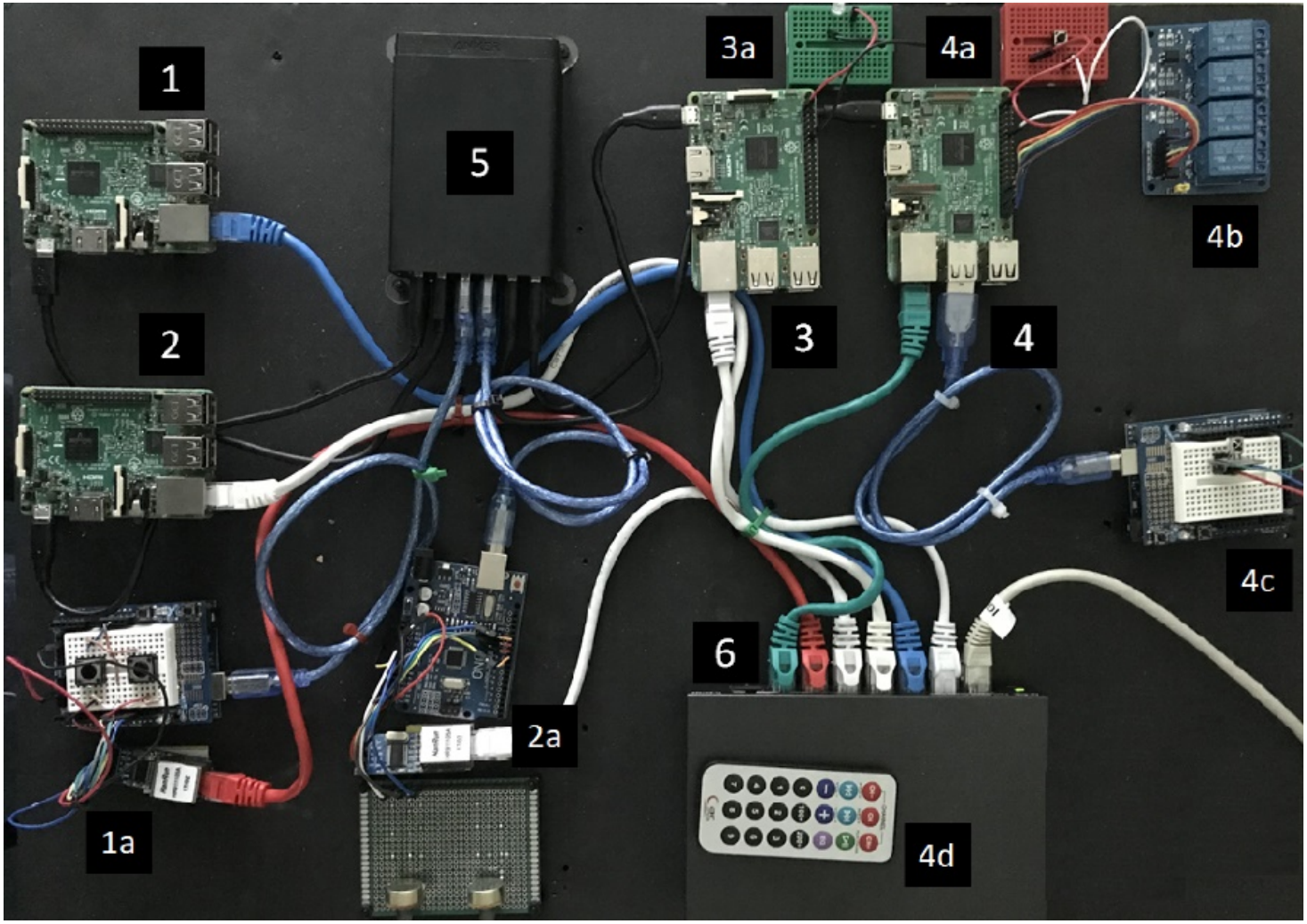
5.6 Testbed ECU and Sensor Hardware

To accurately model a vehicle central locking mechanism, hardware is required to replicate various automotive ECUs and their attached peripherals. The Raspberry Pi has been used to simulate an ECU in previous research into embedded systems and engine management (Walter et al., 2014; Vaughan and Bohac, 2015). The Raspberry Pi is a low-cost single-board ARM-based processor computing device. It can accommodate a wide range of Graphic User Interface (GUI) as well as minimal text-based operating systems. At the time of building the testbed system the Raspberry Pi version 3 was the latest iteration of hardware and had the necessary computing resources to accommodate the container software (Krylovskiy, 2015; Hurst et al., 2017; Johnston and Cox, 2017). Like an ECU, the Raspberry Pi benefits from many available GPIO pins and through these can directly interact with externally connected hardware and other embedded systems. The Raspberry Pi is an ideal hardware platform to simulate an automotive ECU applicable to this research. The Raspberry Pi and Arduino's specification in this research can be found in Appendix F.

To test containers accurately within an automotive E/E architecture context, the modelled central door locking function must closely replicate an existing automotive system. Several dedicated ECU hardware platforms are required to separate the individual and independent ECU functions across several different automotive domains. The modelled system requires four control systems and associated transactions, these include:

- Gear ECU function - part of the transmission domain.
- Acceleration ECU function - part of the engine domain.
- Door Control ECU function - part of the body domain.
- Light Control ECU function - part of the body domain.

Each of the identified ECU functions is hosted on its own individual Raspberry Pi hardware platform and is connected via a network to model cross-domain functionality]. Each Raspberry Pi is responsible for specific data collection and subsequent processing. Figure 29 depicts the testbed layout of the ECU hardware and attached peripherals.



System Number	System
1	Gear ECU
1a	Gear Select Sensor
2	Engine ECU
2a	Accelerator Sensor
3	Light ECU
3a	Exterior Light
4	Door ECU
4a	Collision Sensor
4b	Door Lock Relays
4c	IR Receiver Sensor
4d	IR Sender / Fob
5	System Power Supply
6	In-vehicle Network Hub

Figure 29: ECU central locking function testbed hardware

Several attached sensors provide the initial simulated automotive data. Actuators provide the door locking mechanism and LEDs that simulate vehicle lights. The modelled system requires specific peripheral hardware that includes:

- Central door locking mechanism - provided by a four-channel relay module. Each relay represents a specific vehicle door. The vehicle doors are locked when the corresponding relay is in the closed position.
- Remote door lock trigger - manual door states are affected via a remote IR transmitter device. The IR transmitter sends one of three selectable door commands to an IR receiver. This particular functionality is suspended if the current transmission state is in any gear other than neutral.
- External lighting - an LED simulates the vehicle headlights, which illuminates according to the received door state.
- Gear position – the current selected gear is represented by a series of depressions on one of two pushbutton sensors that either increase or decrease the gear.
- Vehicle acceleration – the simulated engine r/min is selected by a potentiometer position setting with a data range of 0 – 1024.
- The collision sensor – a push-button sensor simulates the deployment of an airbag or activation of a collision sensor and when pressed, activates the overriding safety mechanism.

Several system peripheral devices are directly connected via the GPIO pins of a particular ECU. Other peripheral devices are connected via Arduino programmable circuit boards where raw sensor data is collected, processed and subsequently transmitted to the relevant ECU via a simulated in-vehicle network. Figure 31 is a block diagram of the modelled door central locking function simulation.

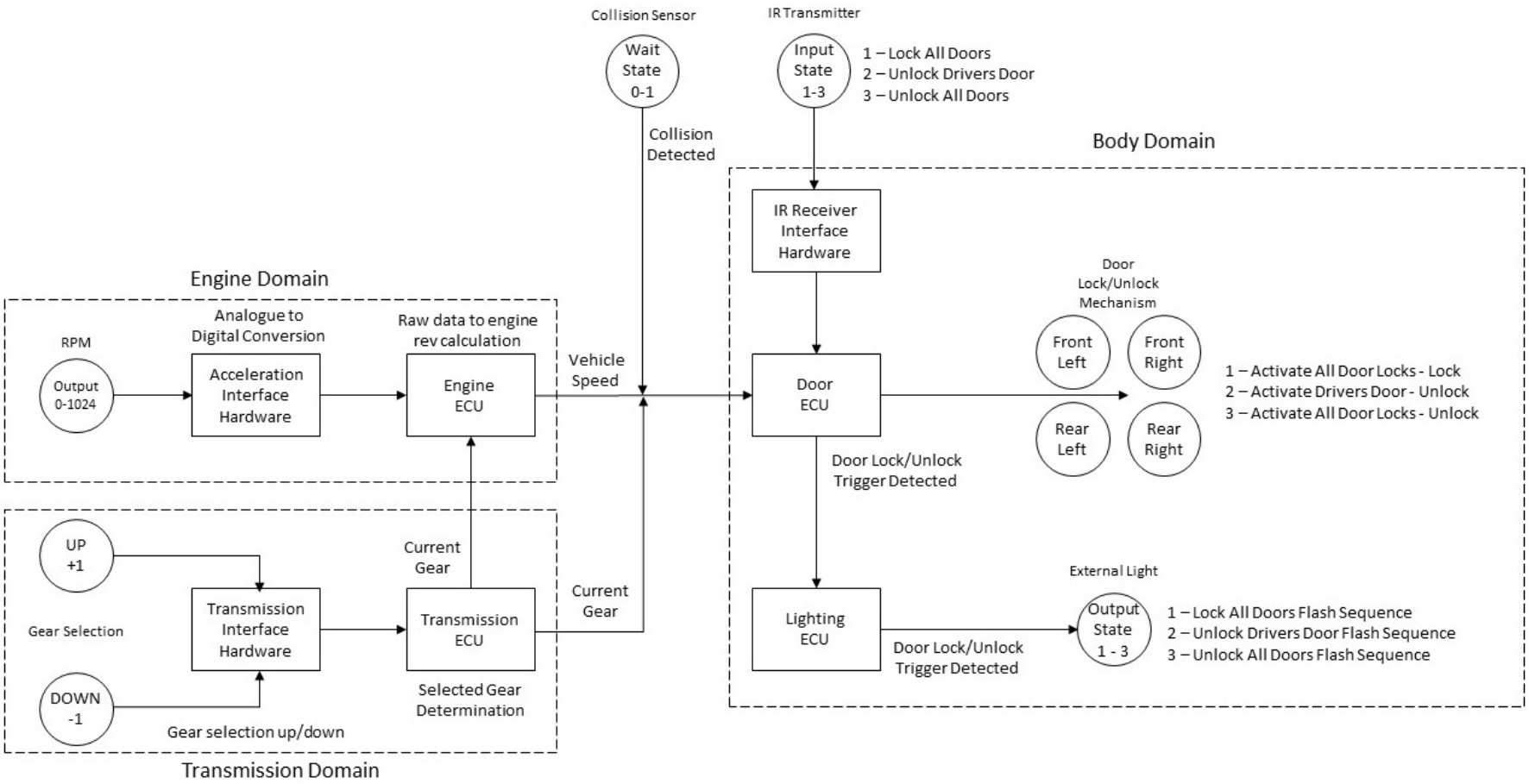


Figure 30: Testbed door central locking function

5.7 Testbed ECU Software

Each simulated ECU requires a specific software program that provides a particular vehicle function. To accomplish this, each testbed ECU needs an operating system, network stack, GPIO pin access and a high-level programming language.

5.7.1 ECU operating systems

There are several operating systems tailored for use with containers. All are highly optimised Linux distros and offer a small footprint with minimal additional software packages, system utilities and services, and no GUI desktop environment. These optimised container distros include Alpine Linux, RancherOS, CoreOS and VMWare Photon OS. Except for CoreOS, all are compatible with running on the Raspberry Pi with most of these distros falling into the sub 100MB footprint. A fully optimised ECU operating system is an essential factor for a live ECU environment. As such, a generic operating system will be used to provide the flexibility necessary to install any required additional software tools and monitoring programs. The Raspbian Lite OS provides a reduced text-based version of Raspbian and utilises fewer system resources than the GUI version. Raspbian Lite is a Linux Debian-based operating system which is highly optimised to the Raspberry Pi and approximately 300MB in size compared with the full version of Raspbian which is approximately 1.3GB in size.

Alpine Linux, RancherOS, CoreOS and VMWare Photon OS are all optimised OSes which include a container virtualisation technology known as Docker. However, there are limitations with these OSes, for example:

- Alpine Linux, although a popular OS choice where container virtualisation is concerned, is more suited to run within containers rather than as a hosting platform for container virtualisation.
- CoreOS is more suited towards large container-based applications. This OS requires a proprietary orchestration system which is not required for this research.

Raspbian Lite is a complete general-purpose OS for the Raspberry Pi and incorporates all of the components required to run a container environment, network stack and the necessary software monitoring tools.

Container system resource use is a crucial factor addressed by this research, with OS functionality being preferable to an optimised embedded OS.

5.7.2 Functional programming scripts

Each ECU runs an identically configured OS but each ECU has its own individualised software program that implements ECU system functionality. Each ECU within the testbed is responsible for its own dedicated function but is often required to transmit data to other ECUs depending upon the given task. In the automotive world, the high-level programming language of choice is C. There are numerous software programming standards surrounding the use of this particular programming language, which ensure that any harmful programming routines and code do not put the vehicle in an unsafe state, especially regarding safety-critical vehicle functions.

Python is an interpreter-based language and supports object-orientated, procedural and functional programming. Although Python is slower in comparison to compiler languages (including C), this research utilises Python. It is an ideal programming language on the Raspbian Lite OS because it offers high flexibility when accessing GPIO pins. In order to model the central locking system, each ECU requires a specialised Python script that provides individual ECU functionality (i.e. gears, lights, engine and doors). When combined, these simulate the central locking mechanism. By utilising Python multi-threading in this way, the hardware is able to execute code faster, thus promoting operational efficiency.

The literature demonstrates that as the number of lines of code increases with each new vehicle model, so do inherent errors. As such, each application script will be designed with minimal coding to keep the script size as low and as efficient as possible. Minimal and efficient code has less of an impact on available system resources. Previous chapters have highlighted the relationship and associated problems concerning ECU hardware resource constraints and high automotive software optimisation levels. Although the Raspberry Pi has large amounts of available resources, it is necessary to keep the functional software code to a minimum to promote code efficiency within a live automotive system.

5.8 Research Testbed Build Stages

There are several procedural and functionality stages required in order to implement a fully functional modelled central locking system.

5.8.1 Testbed procedural build stages

The identified high-level procedural stages required to build and implement a simulated central locking/unlocking function into a suitable testbed include:

1) Installation and configuration of a base OS image on four suitable simulated ECU hardware platforms.
2) Installation of required sensors to produce simulated automotive system raw data
    a) Potentiometer - vehicle accelerator pedal simulation.
    b) Switches - vehicle gear selector simulation.
    c) IR receiver - vehicle IR sensor.
3) Installation and configuration of three Arduino prototype boards to acquire and perform initial processing of raw sensor data.
    a) IR receiver ECU interface.
    b) Gear selector ECU interface.
    c) Acceleration ECU interface.
4) Development of four individual Python scripts to simulate ECU application software.
5) Configuration of an Ethernet-based network (simulated in-vehicle network) to enable ECU communication.

5.8.2 Testbed functionality build stages

The following stages list how the simulated system works and interacts:

1) Initial system power-up is provided by a single power supply which simulates the vehicle ignition key process.
2) Each ECU boots their own operating system.
3) Arduino prototype boards powerup and load program code into flash memory.

4) Automotive software automatically loads after system boot up.
5) Arduino prototype boards collect and process raw data.
6) Transmission of processed data to the corresponding host for ECU functional data processing.
7) ECU data is processed and produces corresponding output for isolated ECU functionality.
8) Processed data where required is transmitted to relevant waiting ECU for processing.
9) Distributed process data is processed and produces corresponding output for distributed ECU functionality.

5.9 Testbed Individual System Functional Testing and Data Verification

To ensure the test system will meet the specified system requirements, several tests will be undertaken to confirm that each subsystem works correctly, as well as overall system functionality.

5.9.1 Engine ECU

The Engine ECU process requires data from the accelerator sensor as well as the Gear ECU. The modelled accelerator sensor within the testbed system utilises a potentiometer. The accelerator sensor is connected to an Arduino development board which when system power is applied automatically runs a script to collect raw sensor positional data from the accelerator sensor. The potentiometer's resistance is measured through its full range of motion and compared with the stated hardware specifications to ensure that the potentiometer's accuracy in operation and the sensor readings are correct. To verify that the data received by the Arduino development board is accurate, the in-built Arduino sketch serial monitor will be used to confirm that the analogue to digital conversion of the raw sensor data is being recorded and converted accurately, depending upon the potentiometer setting.

The Engine ECU application script receives data from its dedicated sensor and compares it against a series of predefined instructions. The accelerator sensor setting determines the simulated engine revolutions (r/min). Although this ECU requires two different data values to generate a simulated vehicle speed, the Engine ECU program will still produce and display a r/min value based on the received accelerator sensor data.

5.9.2 Gear ECU

Gear selection simulation utilises two push-button switches. The switches select a gear sequentially either up or down through the gear range. In standard gear stick operation, gears can be skipped during driving. The testbed gear selection process simulates a sequential gear selection mechanism rather than a gear stick operation selection procedure. An Arduino development board automatically runs a script and collects raw data from the gear sensor gear selection. To verify the data collected by the Arduino development board, the output of the push button switches will be observed using the Arduino serial monitor process to ensure that each button press is registering as a gear selection.

The Gear ECU application script receives data from its dedicated sensor and increases or decreases the current gear number depending upon the data it receives from the push button switch sensor. The last gear number, including the previous gear, is displayed as part of this ECU functionality. The final gear number is subsequently transmitted to the Engine ECU, to calculate vehicle speed. The same data is also sent to the Door ECU as part of the automatic door lock/unlock function. Confirmation of the current gear is displayed on the Engine ECU output display.

5.9.3 Light ECU

The Light ECU function is activated when the IR receiver detects a signal from the transmitter. The engine or Gear ECU does not trigger the operation of this ECU. Data about the door state is sent from the Door ECU. The Light ECU script compares the received code to one of three states and actives the appropriate light flash sequence according to the received state. If the data received do not match any of the three coded conditions, the system will not operate.

5.9.4 Door ECU

The Door ECU has two specific modes of operation: automatic and manual lock/unlock activation. These two modes are triggered depending upon the current door state and received data relating to a change in that state.

5.9.4.1 Central locking function: manual mode

In this mode, the system is activated by an IR receiver that reads a code generated by an IR transmitter. To check the initial data gathered via the Arduino development board, the IR transmitter's output will be observed via the Arduino serial monitor to ensure that each button press registers the correct factory set code. The Door ECU application script receives data from its dedicated sensor and compares the received code to one of three manual conditions. If any match, the current door state is displayed and the relevant data is transmitted to the Light ECU and attached relay board which activates the door locks accordingly.

5.9.4.2 Central locking function: automatic mode

The system activates under two automatic trigger processes – gear selection or vehicle speed. The Door ECU receives data from the Engine ECU relating to the vehicle's speed and the Gear ECU relating to the current selected gear. In automatic mode, the door mechanism activates when one of three specific conditions are met:

- Vehicle speed equals or exceeds 50km/h.
- Vehicle’s current gear is ≥ 3 and the current speed is less than 50km/h.
- Vehicle’s current gear is neutral.

The script has conditions relating to vehicle speed and current gear. If either of these conditions is met the locking mechanism triggers. The locking mechanism trigger state will be verified by observing the Engine ECU output when the door lock mechanism is activated. This output relays the current selected gear as well as vehicle speed.

5.10 Chapter Summary

This chapter proposes that in order to test the validity of a container-based E/E architecture, a suitable modelled distributed automotive function is required. An automotive process that incorporates data from several different domain-based ECUs is an ideal candidate to meet this research's requirements and will be achieved through a vehicle door central locking process. A modern central locking system has numerous dependencies and related sub-functions that require data from distributed and isolated processes across several automotive domains. Several different trigger mechanisms provide cross-domain ECU communication from the engine and transmission automotive domains, and will accurately replicate a live central locking function. This type of system often requires a combination of real and non-real time data to accomplish the primary function of locking and unlocking selected vehicle doors. Within this chapter, the modelled process and associated trigger mechanisms have been mapped using functional architecture and a flow diagram. From this analysis, a suitable hardware platform has been chosen to replicate the required system ECUs and associated hardware peripheral sensors. Lastly, ECU application scripts have been coded that provide individual ECU functionality.

Chapter 6 System Resource Evaluation

Objectives

- Provide an overview of the system tests undertaken within this research.
- Measure and compare native and container CPU and memory saturation.
- Measure and compare native and container CPU and memory utilisation.
- Provide an overview of which system resource is best suited to a container-based ECU.
- Provide an overview of consolidation through bound process types

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6.1 Introduction

Container-based virtualisation has many benefits as illustrated in Chapter 4. However, if the proposed architecture underperforms in the context of system resource use (which includes CPU, memory and OS kernel), it may be unsuitable for an automotive ECU application. This chapter investigates how containers utilise available system resources, particularly processor and memory, as these are essential system resources, especially within real-time systems where timing is fundamentally linked to safety. The following tests in sections 6.7 and 6.8 are divided into two main categories of saturation and utilisation. Both are essential metrics when determining overall system performance and resource use (Gregg, 2013). For each of the three test modes (base, native and container), CPU and memory statistics were measured under both saturation and utilisation categories. This chapter concludes with a series of tests investigating consolidation through containerisation, where both native and container test performance is studied when external stress loads are applied to the system.

6.2 ECU System Testing

As part of the requirements and testing phases of hardware and software development, the automotive industry utilises “in the loop” testing mechanisms (Leen et al., 1999; Ebert and Jones, 2009). There are a variety of in the loop mechanisms, including:

- Model In the Loop (MIL) testing is used to develop system and controller models to determine if the modelled controller can control the logic, inputs and outputs between the controller and the system.
- Software In the Loop (SIL) testing is concerned with aspects of the automotive functional software. Software behaviour can be tested and validated in a modelled hardware environment before actual hardware prototyping stages. This form of testing determines the necessary hardware requirements to support operating software and detect coding errors.

- Processor In the Loop (PIL) testing uses cross-compiled code to test code execution and responses from the processor architecture. This testing type detects code compiler or processor architecture faults.
- Hardware In the Loop (HIL) aides in configuration development and testing of new ECU hardware. New ECUs connect to a HIL test system which provides a simulated environment. Any actual physical hardware is electrically modelled and software algorithms provide the necessary data parameters. A HIL test system produces the same data outputs as a real engine. This data is then inputted into the connected ECU to test its hardware and functional software under specific loads.

This research is concerned with validating containers as a mechanism to host multiple ECU software functionalities within a future automotive E/E architecture. However, this research was prohibited from using any of the above identified in the loop testing mechanisms because of cost and lack of availability. Instead, an automotive central locking mechanism was selected to provide a suitable test environment, as outlined in the preceding chapter. The testbed environment modelled existing automotive ECU systems, incorporating specific hardware and necessary software scripts written to provide the modelled automotive functionality.

6.3 ECU Test Modes of Operation

The CPU and memory resources required and consumed by an ECU function are predictable and determined during the design and testing stages. This research proposes a container-based ECU architecture which in implementation requires additional software and level of abstraction between the application software and underlying hardware. By measuring the specific system resource use, an understanding can be gained of how additional resources are required to support a container-based automotive architecture when compared with current ECU configurations. To determine the additional resources necessary for a container-based system, a series of test comparisons must be performed against three identified system operational modes. These include:

6.3.1 Base system test mode

This initial test mode establishes a baseline benchmark of the system resources used when the modelled ECU is in an idle state. Only the active processes relating to OS operation after system initialisation are in execution. Any system overhead introduced by the ECU software across subsequent test modes can be compared to this baseline set of results to determine the overheads when the ECU functional software is executed natively and within a container.

6.3.2 Native system test mode

This test mode generally mirrors current automotive E/E architectures and ECU function operations. Native system test mode is an extension of the base system test, including any additional processes initialised by the ECU functional software. The same resource tests that run across all four modelled ECUs during the base system tests are repeated in this test mode. During this test mode, the results will show specific increases in system resource use when each ECU functional software is in execution compared with the base system test.

6.3.3 Container system test mode

ECU software executing during the native test mode runs directly on top of the ECU OS. During the container test mode, individual containers encapsulate the ECU functional software and any additional software dependencies required for its operation. This test mode measures any other system resources or resource overhead required to run the ECU software within a container when compared with native operation.

6.4 Test Measurement Methodology

Two crucial system resources within any automotive ECU are the system processor and available memory. These two resources and how they are used are fundamental aspects of this research. A set of test criteria must be defined to ensure the same conditions are applied across all resource tests during the three test modes. Best practice for data capture involves evaluating each specified metric over multiple data

collection instances and particular time frames, to fully understand the specific system resource usage. Specific test times are divided into three distinct time frames (60-second, 600-second and 1200-second duration), as described below:

- Δtime_60 = 60-second sample run - some tests investigate the specific resource use required during the ECU software's initialisation. Thus, only the first few initial seconds are required for analysis. A 60-second test run is a sufficient time to allow for an initial warm-up period before script execution.
- Δtime_600 = 600-second sample run – these tests investigate the functional software's entire lifecycle from initialisation to termination. These time frame tests include a system idle warm-up period of 30 seconds, which eliminates any spikes in specific resources associated with the initial stages of software execution. Script execution time for these timed tests is 500 seconds, at which point the script terminates, with the final 30 seconds of the test being the cool-down period. CPU and memory resource levels after script execution are a crucial area of investigation. They reveal whether the system returns to a similar state before the script was executed. It is important to understand the level of resources which are not released back to the system after execution, particularly ECU systems that only activate periodically to accomplish a specific task or function.
- Δtime_1200 = 1200-second sample run – this test period investigates resource use trends over an extended time to see if there are specific increases during long execution cycles. However, to display this information, the published results must be a cross-section of the entire 1200-second test, especially where test results show little to no observable activity.

The flowchart below illustrates the procedural steps taken during each test.

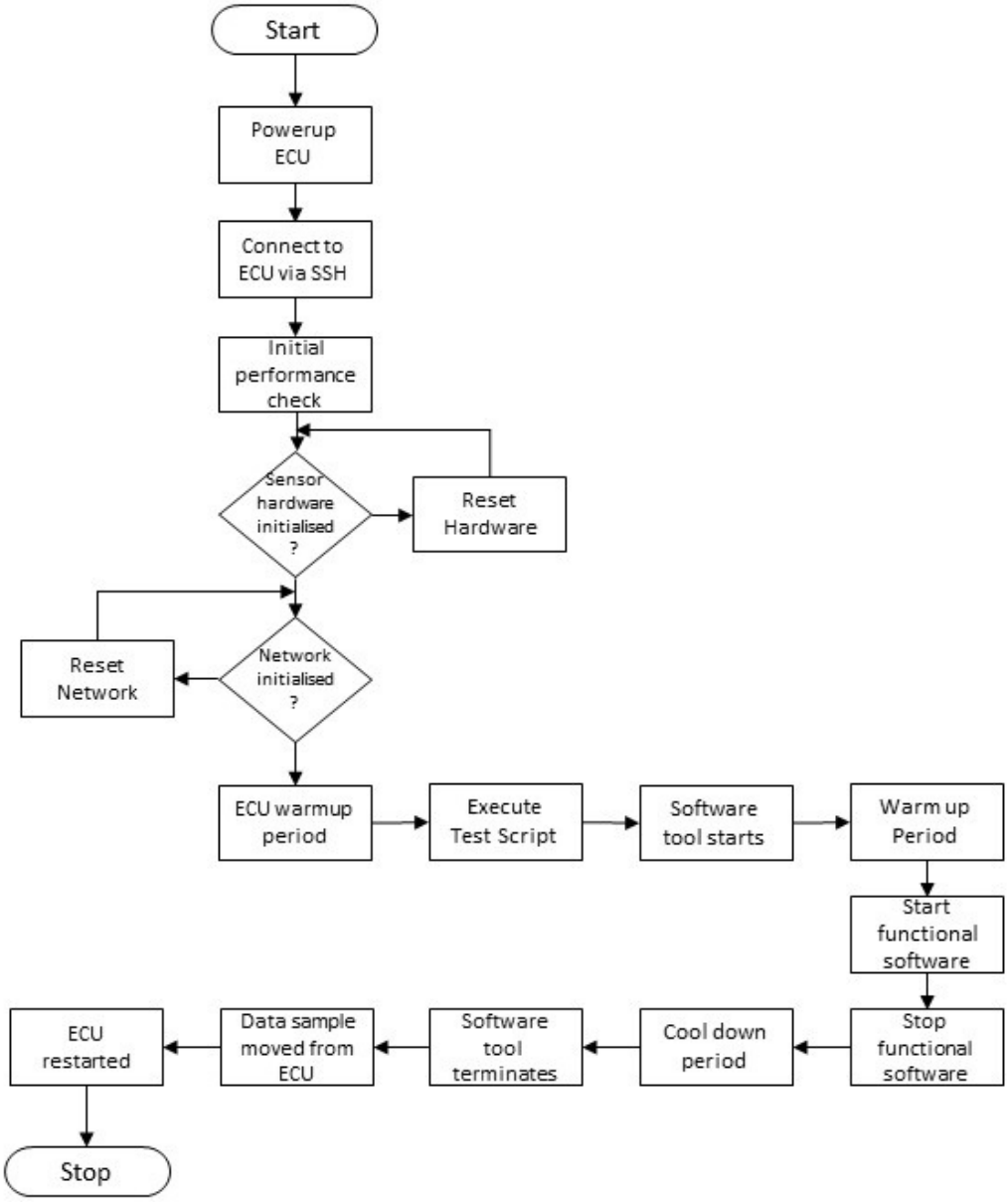


Figure 31: Test Plan Procedure

6.5 Key System Performance Metrics Overview

This research draws comparisons between the current automotive E/E architecture and traditional client-server architectures. In supporting a server environment, the Utilisation, Saturation and Errors (USE) methodology can investigate performance issues and potential bottlenecks (Gregg, 2013; Hartmann, 2017). The Rate, Errors and Duration (RED) method can also be used to monitor microservices (Wilke, 2017; Jackson, 2018). A combination of these two methods provides an ideal methodology for monitoring the specific resources to support native and container-based ECU execution. However, it is not necessary to utilise the errors component of the USE method nor the rate and errors components of the RED method because these are more focused metrics for a web-based application. This research, therefore, combines elements of the USE and RED methods, adopting a new methodology. In particular, it focuses on Utilisation, Saturation and Duration (USD) components to identify performance across the target system CPU and memory. The critical metrics for this research includes:

- Utilisation – the percentage of time a resource is busy compared to when that resource is available over a given time interval.
- Saturation – the amount of work that is queued or waiting for an available resource, often expressed as a queue length.
- Duration – the amount of time spent serving a request.

6.6 CPU and Memory Monitoring Tools

Numerous Linux software monitoring tools are available that measure key CPU and memory metrics. In turn, these specific resources can be observed by applying the USD methodology to each ECU. The following software tools can be used to monitor and record CPU and memory saturation for each modelled ECU when an ECU system is idle and when the automotive function is running in both native and container operational modes. The software tools that are used to monitor and record the key system metrics are listed in the figure below and Appendix A.

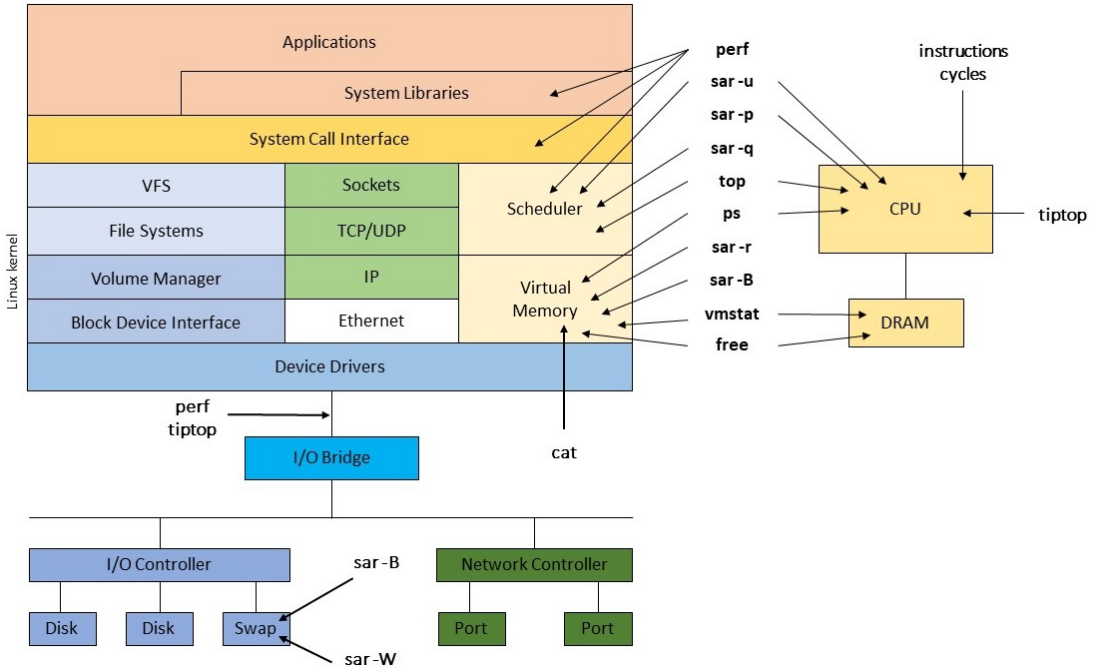


Figure 32: Software Tools and Architectural Areas of Testing

6.6.1 *vmstat* (virtual memory statistics)

vmstat is a useful tool for identifying potential resource bottlenecks and corroborates the data collected from several other monitoring tools. The metrics monitored include:

- The number of processes/tasks waiting runtime (R state) and those in interruptible sleep (D state).
- The amount of free or idle system memory.
- Memory swap information.
- CPU statistics including %us, %sy and %id.

```
ECU001:~$ vmstat
procs -----------memory---------- ---swap-- -----io---- -system-- --------cpu--------
 r  b   swpd   free   buff  cache   si   so    bi    bo   in   cs us sy id wa st
 0  2      0 3616004 226020 1910914    0    0   104    33  470 1546  9  4 87  0  0
```

Figure 33: *vmstat* sample output (ECU001)

6.6.2 *free* (free and used memory)

This tool displays various memory statistics, including the total available free memory, used swap and physical memory. Other observed metrics from this software monitoring tool include the buffers column that reports the amount of allocated memory in use. The cache column reports the amount of allocated memory swapped to disk or unallocated if other tasks require that resource.

6.6.3 *pmap* (process memory map)

pmap is a simple software tool used to monitor total memory use in kb of individual processes.

6.6.4 *cat* (concatenate files)

The *cat* command obtains OS kernel schedule statistics regarding individual processes. The values obtained from the *schedstat* are a snapshot of the average time totals a process has spent on the CPU and waiting for an available time slot on the CPU at the point when the *cat /proc/<pid>/schedstat* command is run.

The schedule statistics *schedstat* describes three statistics which define overall scheduling latency:

- Sum of time spent running processes in the processor.
- Sum of time spent waiting to run a task (often measured in jiffies).
- The number of time slices or voluntary and involuntary switches running on the CPU.

Automotive ECUs often have real-time operational requirements which habitually relate to system safety. Understanding the overall scheduling latency between the native/bare metal and container ECU operational modes is a crucial factor of this research.

6.6.1 *sar* (system activity reporter)

The *sar* monitoring tool is used extensively throughout this research. It is vital for monitoring ECU resource use for both CPU and memory saturation and utilisation. Figure 33 is an example *sar* output. The following configuration flags can be applied to this tool to monitor and record specific CPU and memory saturation and utilisation metrics:

- *sar -B* - reported system paging statistics.
- *sar -q* – monitors CPU load, run queue and process list lengths.
- *sar -R* - monitors general memory statistics.
- *sar -r* - reports on the percentage of system memory used.
- *sar -W* - monitors swap in and swap out rates.

```
ECU001:~$ sar –q 1
Linux 5.3.0.61-generic  (ECU001)        30/06/20        _X86_64_        (4 CPU)

08:36:23      runq-sz  plist-sz   ldavg-1   ldavg-5  ldavg-15   blocked
08:36:24            0       819      1.46      1.50      1.55         0
08:36:25            0       819      1.43      1.49      1.55         0
08:36:26            0       819      1.43      1.49      1.55         0
08:36:27            0       819      1.43      1.49      1.55         0
08:36:28            0       820      1.43      1.49      1.55         0
08:36:29            0       820      1.43      1.49      1.55         0
08:36:30            0       820      1.43      1.49      1.55         0
08:36:31            0       820      1.39      1.49      1.54         0
08:36:32            0       820      1.39      1.49      1.54         0
```

Figure 34: Example of a *sar* output

6.6.2 *perf* (performance analysis)

perf is a software tool that provides system-wide statistical profiling information for analysing the performance of an application in execution. *perf* enhances understanding of the system scheduler properties (sched latency and sched timehist) that measure latencies at the task/process level and latency events, including the sched-in count, total run time, and average run time per *sched-in* count.

6.6.3 *pidstat* (process statistics)

pidstat is a software tool useful for monitoring individual kernel tasks and corresponding child processes. It displays metrics for specific or all running processes and collects data on time spent by a task executing at the user and system level.

6.6.1 top / htop / nmon

The three software programs *nmon, top* and *htop* are all dynamic software monitoring tools. They all provide real-time data output about many aspects of the host system, including CPU, memory and processes. These three tools validate the accuracy of the results obtained from the other more specialised tools. They provide a real-time monitor for ECU functional software in execution at the process and thread-level and report any other processes invoked during the native and container test modes.

6.6.2 CPU software tool quick reference (see Appendix A)

Test Case	System Resource Monitored	Software Tool	Metric Reference	Reference
All cases	CPU	*htop*	Collaboration and general monitoring tool	Chapter 6
		nmon	Collaboration and general monitoring tool	Chapter 6
Per process		*cat*	Time spent on CPU/time spent waiting on the queue	Page 111
		perf	Average and maximum delay per schedule	Page 113
		pmap	Total memory use	Page 133
		sar	Percentage per CPU idle time	Page 117 - 122
			Percentage per CPU system processes	Page 117 - 122
			Percentage per CPU user processes	Page 117 - 122
		tiptop	Instructions per cycle	Page 123
System		*perf*	Total number over a sample time period	Page 125
		sar	Number of tasks awaiting runtime	Page 99 - 100
			CPU time per %system processes	Page 117 - 122
			CPU time per %user processes	Page 117 - 122
			Number of tasks in the task list	Page 102
			load average 1/5/15 min	Page 106 -109
			Context switches per second	Page 125
		vmstat	Number processes in sleep (D state)	Page 99 - 100
			Number processes waiting runtime (R state)	Page 102 - 103
			Percentage of ALL CPU system processes	Page 117 - 122
			Percentage of ALL CPU user processes	Page 117 - 122

Table 3: CPU software tools quick reference

6.6.3 Memory software tool quick reference (see Appendix A)

Test Case	System Resource Monitored	Software Tool	Metric Reference	Page Reference
All cases	Memory	*top*	Collaboration and general monitoring tool	Chapter 6
Per process		*cat*	Minor faults	Page 131
		pmap	Process memory map Size of map in Kb	Page 135
		sar	Total and major faults per second	Page 131
		smem	Unique set size memory	Page 135
System		*free*	Free memory	Page 135
			Used memory (total-free-buffers-cache)	Page 135
		ps	Minor page faults	Page 131
		sar	Memory frame pages per second	Page 126 - 127
			total memory used	Page 133 - 134
			Buffer pages per second	Page 127
			Number of pages scanned/s	Page 117 - 118
			Number of swap pages the system brought out per second	Page 130
			Cache pages per second	Page 128
			Major faults per second	Page 131
			Total page faults per second	Page 131
		smem	Unique set size memory	Page 135
		vmstat	Idle memory	Page 133 - 134

Table 4: Memory software tool quick reference

6.7 CPU Saturation Tests

CPU saturation is the amount of extra work that cannot be serviced by the CPU and has to be queued, thus adding latency (Gregg, 2013). CPU saturation is a crucial metric in determining overall system performance. A CPU is considered saturated when the system load average increases to a value above the number of system processors/cores and maintains that value for an extended period of time. In this instance, CPU load is calculated as the sum of processes in execution or waiting for execution at any given time. A system which is oversaturated experiences:

- A longer wait for a process in an idle or wait state.
- An increase in overall request-response times.
- A subsequent increase in CPU utilisation.

Therefore, CPU saturation also refers to the number of processes, either queued or blocked awaiting CPU time. If the number of instructions to be processed is more than the processor can accommodate due to its speed, the program in execution is considered CPU bound. An example of a CPU bound process is an algorithm which requires a large number of calculations that hold the CPU for as long as the scheduler allows. The saturation tests conducted as part of this research use the standard inbuilt OS scheduler (SCHED_OTHER), a conventional timed-shared process. The following set of load and queue length tests display the difference in saturation load placed upon each of the modelled automotive ECUs depending on the system mode of operation - base, native or container.

6.7.1 CPU run queue size (*runq-sz*) tests

The CPU queue length parameter (*runq-sz*) is the number of processes that are ready to run but paused, waiting for CPU time allocation. This parameter has been used widely, for example by Pan et al., (2010) for black-box data collection and monitoring, and Tichy and Zemanek (2001) to monitor and diagnose CPU bottlenecks in the UNIX operating system. Pengfei and Lanfeng (2016) state that the *runq-sz* "reflects the change situation of the physical host's instantaneous load…. so, the instantaneous reference value has more significance" when determining system load. The *runq-sz* can hold more significance than the overall system load average, reflecting the CPU load average over a 1, 5, and 15-minute time frame. In contrast, *runq-sz* refers to the physical host's instantaneous load. Individual ECU runq-sz tests can be found in Appendix B.

A high *runq-sz* value indicates that the system is CPU bound and therefore starved of CPU time. A base test *runq-sz* shown in Chart 1 was conducted over a 1200 second (20 minutes) time frame to understand the number of waiting processes when the system was in an idle state and where only the operating system was in execution. When analysing the data from this 1200 second baseline test, the results reveal very little activity on the CPU run queue, as expected. Over the entire 1200 second test run, the system peaked at two waiting tasks on five separate occasions.

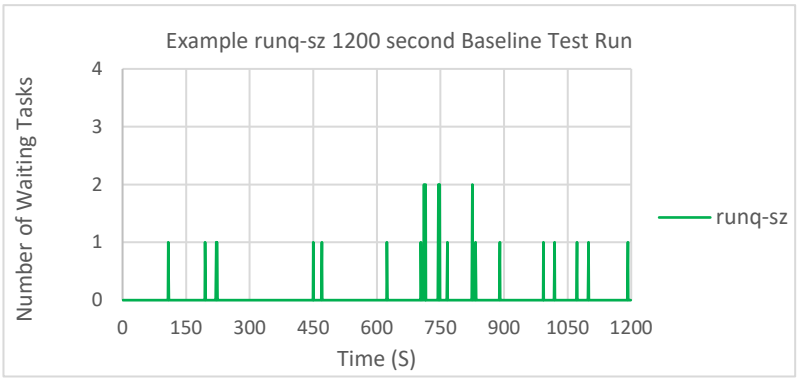


Chart 1: Example baseline *runq-sz* test

The native and container ECU tests were also run for the same 1200 seconds. ECU functional software was automatically executed midway through each test to allow for an extended period of the initial system and post-execution system settling. Additional peaks in the number of R state tasks/processes were expected to be observed during initial ECU software initialisation rather than as a trend over an extended time frame. The entire 1200 second test result data were not suitable for data analysis and hence the full 1200 second test results were capped between the 500 – 700 second range with software execution occurring at the 600-second mark. The following charts display the individual ECU native and container *runq-sz* test results.

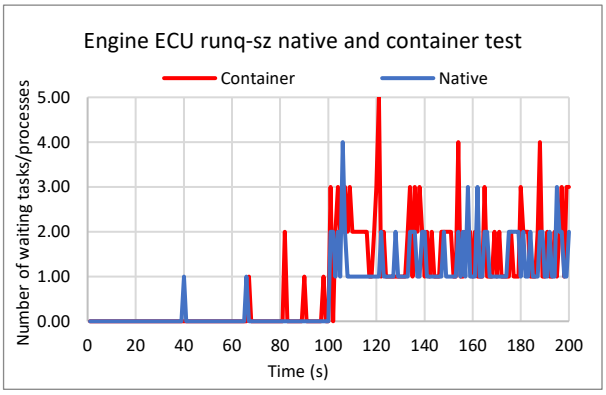


Chart 2: Engine ECU *runq-sz* test

Engine ECU	Native	Container	%diff
Total Tasks	140	177	+21.43
Run Average	1.38	1.72	+24.63
Minimum	0	0	-
Maximum	4	5	+25.00
Tasks = 1	69	49	-23.44
Tasks = 2	29	38	+31.03
Tasks = 3	3	13	+333.33
Tasks = 4	1	2	+100.00
Tasks = 5	0	1	-

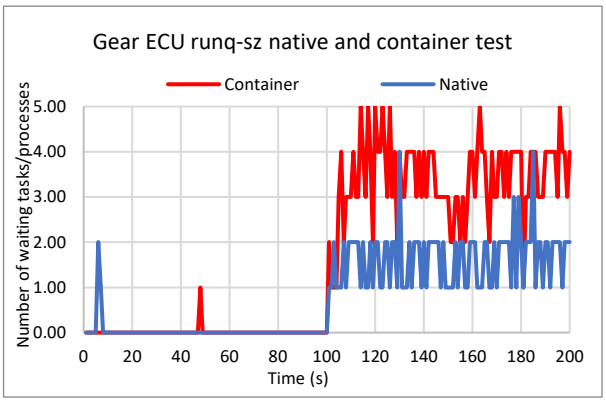


Chart 3: Gear ECU *runq-sz*

Gear ECU	Native	Container	%diff
Total Tasks	168	341	+102.98
Run Average	1.65	3.40	+106.06
Minimum	0	0	-
Maximum	4	5	+25.00
Tasks = 1	42	5	-88.9
Tasks = 2	56	9	-83.92
Tasks = 3	2	37	+1750.00
Tasks = 4	2	43	+2050.00
Tasks = 5	0	7	-

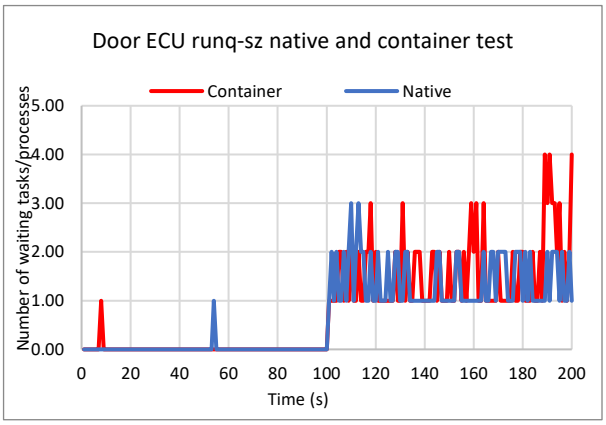


Chart 5: Door ECU *runq-sz*

Door ECU	Native	Container	%diff
Total Tasks	141	149	+5.67
Run Average	1.40	1.46	+4.29
Minimum	0	0	-
Maximum	3	3	-
Tasks = 1	63	62	-1.59
Tasks = 2	36	36	-
Tasks = 3	2	5	+150.00
Tasks = 4	0	0	-
Tasks = 5	0	0	-

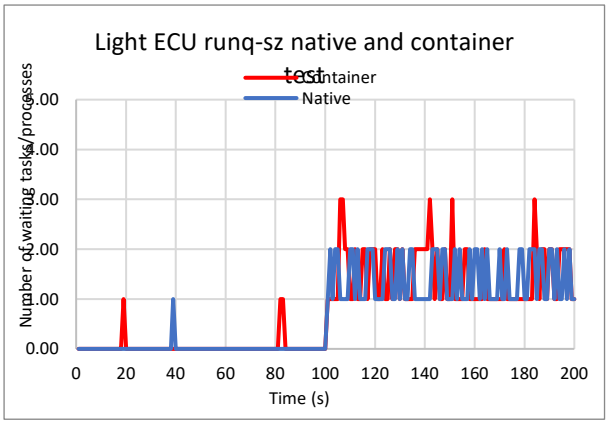


Chart 4: Light ECU *runq-sz*

Light ECU	Native	Container	%diff
Total Tasks	143	159	+11.19
Run Average	1.42	1.58	+11.27
Minimum	0	0	-
Maximum	2	4	+100.00
Tasks = 1	59	58	-1.69
Tasks = 2	42	31	-26.19
Tasks = 3	0	9	-
Tasks = 4	0	3	-
Tasks = 5	0	0	-

6.7.1.1 *runq-sz* test summary

During the container test mode execution, the average number of waiting tasks across all ECUs increased by 58 across the selected time frame. This figure represents an overall increase of 36.56% compared with the native ECU test mode, with peaks observed between 3 – 5 waiting tasks. The individual ECU differences between the two test modes are presented in Table 5 below.

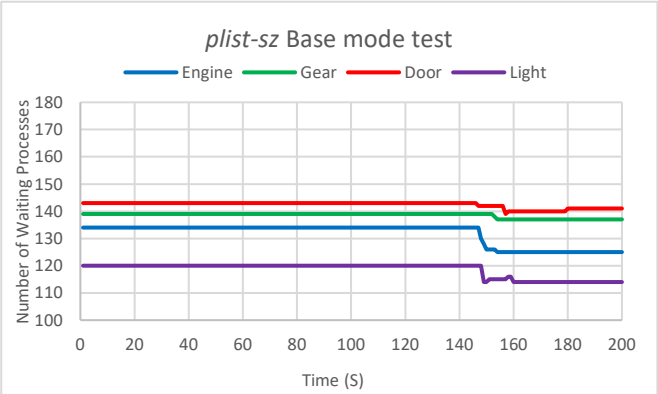
ECU	Container Test Mode *runq-sz* Average
Engine	+24.63%
Gear	+106.06%
Door	+4.29%
Light	+11.27%

Table 5: Container *runq-sz* averages

Only the Gear ECU had an overall increase above the 36.56% average. As observed in Chart 3 above, the number of waiting tasks dropped considerably in the 1 – 2 range and increased in the 3 – 4 range. However, this increase was expected due to the heavy operational workload of this particular ECU. Across the other ECUs, wait queue increases were within the container test mode average.

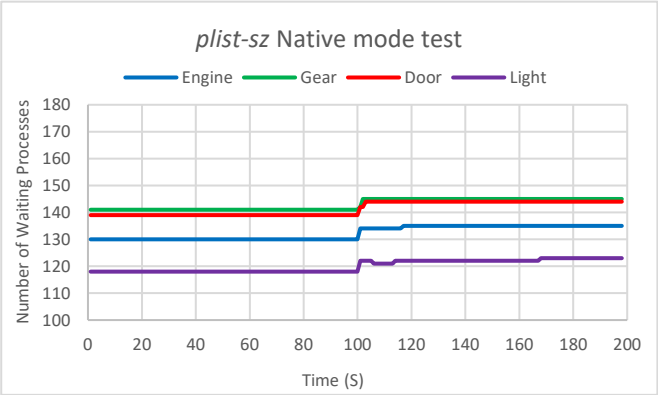
6.7.2 Process list size (*plist-sz*) tests

The process list size (*plist-sz*) displays the number of live processes in execution. As more processes start, this figure increases. The *plist-sz* is a dynamic value - it increases during regular OS operation as new programs initiate new processes and decreases when processes terminate. During ECU operation, this value should remain constant during each operational mode. It was expected that each ECU would produce a slightly elevated number of running and waiting processes upon ECU software initialisation. The following charts and tables highlight the system's process list output during the base test mode across each ECU. These base test results provide the number of running and inactive processes on each of the four modelled ECUs.



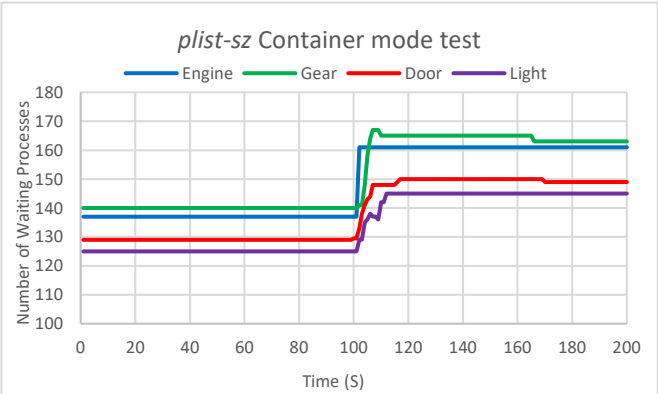
plist-sz	Base ECU Mode			
	Engine	Gear	Door	Light
MIN	125	137	139	114
MAX	134	139	143	120
Average	130	138	141	117

Chart 6: *plist-sz* Base mode test



plist-sz	Native ECU Mode			
	Engine	Gear	Door	Light
MIN	130	141	139	118
MAX	135	145	144	122
Average	133	143	142	120
Base Increase	3.85%	3.62%	0.71%	2.56%

Chart 7: *plist-sz* Native mode test



plist-sz	Container ECU Mode			
	Engine	Gear	Door	Light
MIN	137	140	135	125
MAX	161	167	150	145
Average	149	154	143	135
Native Increase	12.03%	7.69%	0.70%	12.50%

Chart 8: *plist-sz* Container mode test

6.7.3 *plist-sz* test summary

The *plist-sz* test shows the additional processes raised to support the ECU software execution during the native and container test modes. The base test highlighted inconsistencies with the observed data. Each of

the modelled ECUs had identical hardware and OS software configurations. However, there were differences in the additional software required on various ECUs due to specific ECU functions and peripheral hardware interactions, which resulted in an observed increased level of running processes on some ECUs. Across each ECU, the level of processes was consistent with all ECUs experiencing a drop in the number of running processes during the measured base test. The average process count on the process list was 133, with a low of 129 and a high of 134.

During the native test mode, the *plist-sz* average increase across all for ECUs measured 5. However, with only a small number of processes involved in executing ECU functional software, this was expected. Nevertheless, when comparing the total averages across the 200-second test run, the door and Light ECUs exhibited the same or slightly higher overall average increase at 4 and 5 processes respectively. Again, this was due in part to the additional ECU supporting software.

Across the native and container tests, the ECU *plist-sz* average during the script execution was similar to the maximum *plist-sz* values. Once the initial script execution was complete, there were fewer additional increases or decreases observed. The observed increase in the *plist-sz* during the container test across all ECUs was measured overall at an average of 32.92% compared with the native test. During the native test mode, any additional processes raised were solely concerned with the functional software's operation. The container test mode required additional processes to create and maintain the container shell as well as the function software.

6.7.4 CPU load average

The system load average is measured over a 1-minute, 5-minute and 15-minute time frame (*ldavg*-1, *ldavg*-5 and *ldavg*-15) and represents the time the CPU is busy. System load is the portion of work a system performs over a given time frame. If the load is zero, the system is considered to be in an idle state. For each process/task that is either waiting or consuming CPU runtime, the load is incremented by one. During the specified load time frames (1, 5 and 15), the load average is sampled at a default rate of 5HZ/500 ticks which equates to a sampling rate of 5 seconds.

The timed intervals and sample rate are expressed as:

- 1 minute = 5/60.
- 5 minutes = 5/300.
- 15 minutes = 5/900.

Within the Linux kernel, the function CALC_LOAD is periodically called depending upon the defined sample rate. The CALC_LOAD function collects data about CPU load totalling the number of processes in either the R or D state (Bovet & Cesati, 2003). The mathematical expression for this is:

$$load(t) = load(t\text{-}1)\, e^{-HZ/S} + n(1 - e^{-HZ/S}) \qquad 1.2$$

- load(t) – total load over a specific time frame.
- t – time.
- Hz/s – load frequency.
- n – number of load samples.
- e – exponential.

System load is calculated as the average number of processes/tasks running (R state) and the number of processes/tasks in uninterruptable sleep (D state). The *ldavg*-1 metric gives the total number of processes in both D and R states over a 60-second time frame. Both *ldavg*-5 and *ldavg*-15 are extended sampled time frames over 300 and 900 seconds and not the repeated average of the *ldavg*-1 results. Below is a clarification of how each load average is related:

- If the average is 0.00, the system is regarded as being in an idling state.
- If the 5 or 15-minute average is higher than the 1-minute average, overall system load is increasing.
- If the 5 or 15-minute average is lower than the 1-minute average, overall system load is decreasing.

If the load average in any *ldavg* triplet result is greater than the number of system CPUs (cores), it may affect overall system performance. Excessive load on the *ldavg*-1 metric would indicate, for example, short

spikes in resource use due to program execution or excessive paging to disk and as such gives a brief snapshot of the most recent system activity. Suppose the *ldavg*-15 metric is consistently higher than the CPU/core count. In that case, it generally indicates a prolonged increase in the number of R and D state processes. It potentially represents a more persistent and protracted problem with overall system performance.

A CPU or core is considered saturated when the load is 1.0, which equates to the CPU executing at 100% efficiency. Quad-core processors were utilised as a part of this research and therefore, a saturation of 4.0 is considered as running at 100% efficiency on that CPU. The load average shows the overall CPU saturation for the entire system. Anything over 1.0 per CPU/core would suggest that the CPU is in an oversaturated state. Suppose the load average is over 1.0 per CPU/core. In that case, it will undoubtedly have an adverse effect on overall system performance as processes have to wait longer to be allocated CPU time for subsequent execution. Chart 9 and the results table below show the CPU load of the *ldavg*-1, 5 and 15 results during a base test.

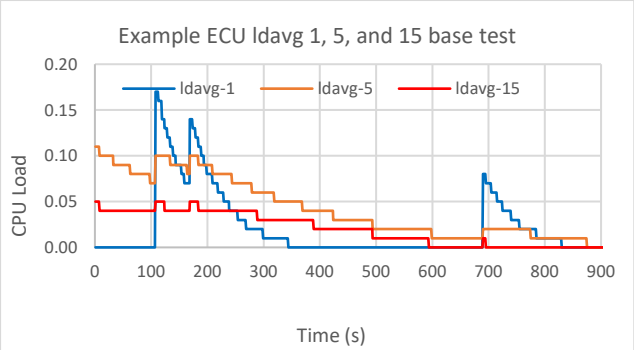


Chart 9: Example ECU *ldavg* triplet test

ldavg (Four Cores)			
ldavg-n	Minimum	Maximum	Average
ldavg-1	0	0.17	0.02
ldavg-5	0	0.11	0.03
ldavg-15	0	0.05	0.02

The results below show the native and container CPU loads across each ECU. To ensure containers are a viable mechanism in hosting ECU functional software within an automotive context, they must not place significant CPU load demands when compared with the native execution of the same software.

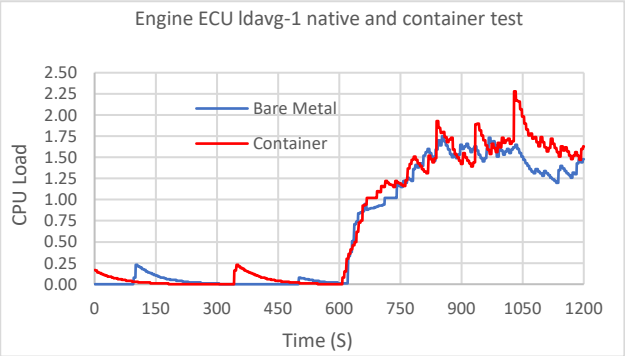


Chart 10: Engine ECU *ldavg*-1 test

ldavg-1				
Engine ECU	Min	Max	Execution Integration	Diff.
Native	0	1.75	772.73	
Container	0	2.28	849.93	77.20
%Difference				+9.99%

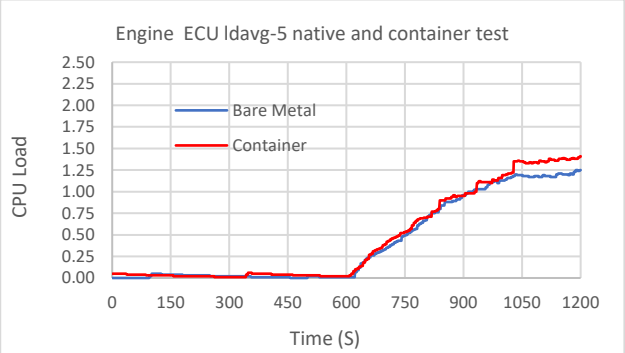


Chart 11: Engine ECU *ldavg*-5 test

ldavg-5				
Engine ECU	Min	Max	Execution Integration	Diff.
Native	0.08	1.25	491.82	
Container	0.01	1.41	535.26	43.44
Difference				+8.83%

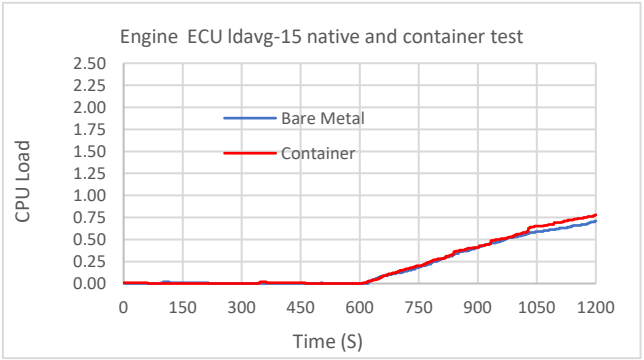


Chart 12: Engine ECU *ldavg*-15 test

ldavg-15				
Engine ECU	Min	Max	Execution Integration	Diff.
Native	0.02	0.71	230.19	
Container	0	0.78	247.45	17.26
Difference				+7.49%

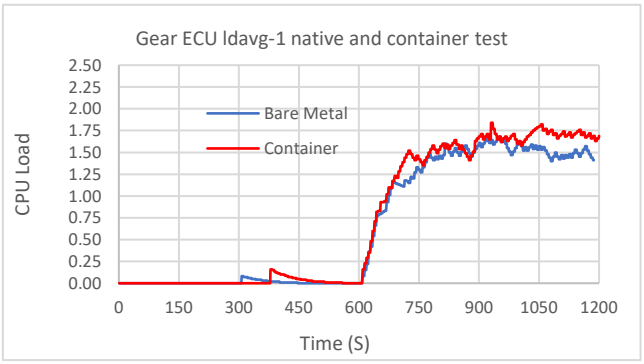


Chart 13: Gear ECU *ldavg*-1 test

ldavg-1				
Gear ECU	Min	Max	Execution Integration	Diff.
Native	0	1.68	802.64	
Container	0	1.84	882.44	79.80
Difference				+9.94%

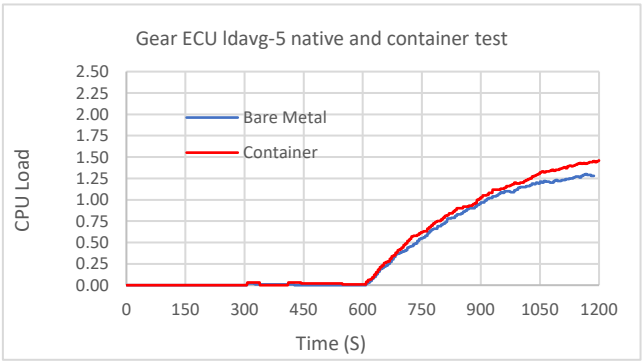


Chart 14: Gear ECU ladvag-5 test

ldavg-5				
Gear ECU	Min	Max	Execution Integration	Diff.
Native	0.08	1.30	509.17	
Container	0.01	1.46	555.89	46.72
Difference				+9.16%

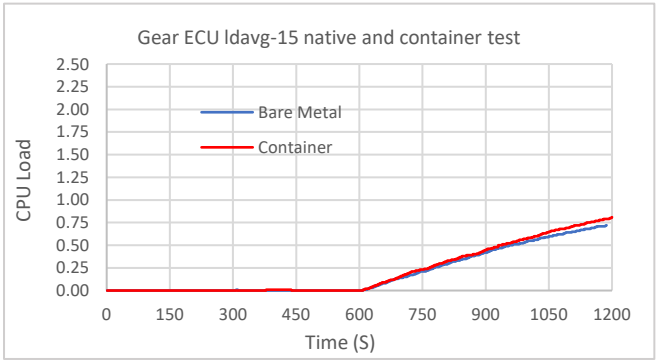


Chart 15: Gear ECU *ldavg*-15 test

ldavg-15				
Gear ECU	Min	Max	Execution Integration	Diff.
Native	0.02	0.71	239.38	
Container	0	0.81	259.34	19.96
Difference				+8.34%

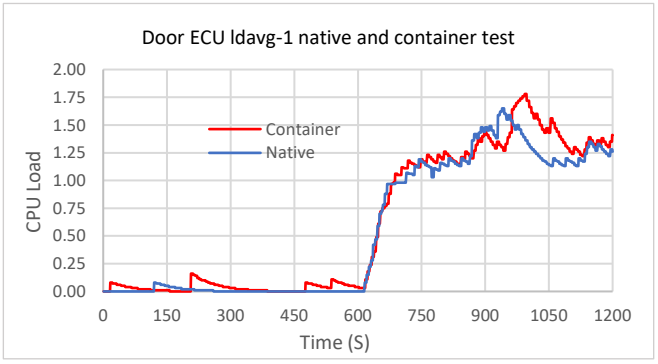


Chart 16: Door ECU *ldavg*-1 test

ldavg-1				
Door ECU	Min	Max	Execution Integration	Diff.
Native	0.03	1.65	683.00	
Container	0.02	1.78	722.48	39.48
Difference				+5.78%

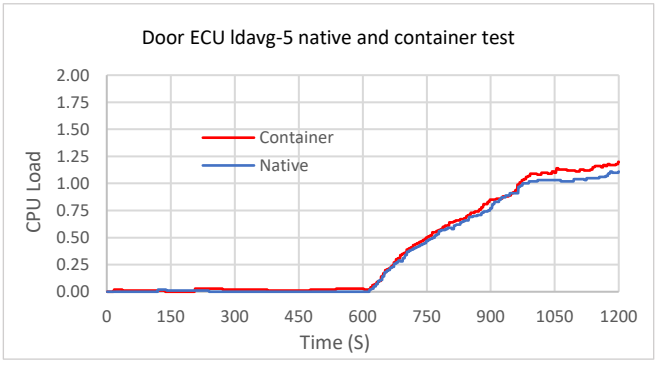


Chart 17: Door ECU *ldavg*-5 test

ldavg-5				
Door ECU	Min	Max	Execution Integration	Diff.
Native	0	1.11	429.20	
Container	0.01	1.20	451.97	22.78
Difference				+5.31%

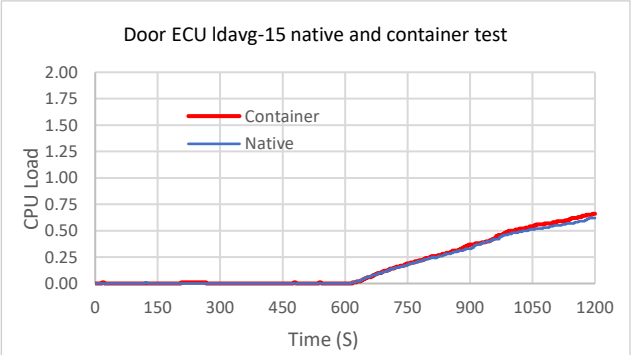


Chart 18: Door ECU *ldavg*-15 test

ldavg-15				
Door ECU	Min	Max	Execution Integration	Diff.
Native	0	0.62	200.96	
Container	0	0.66	211.54	10.58
Difference				+5.26%

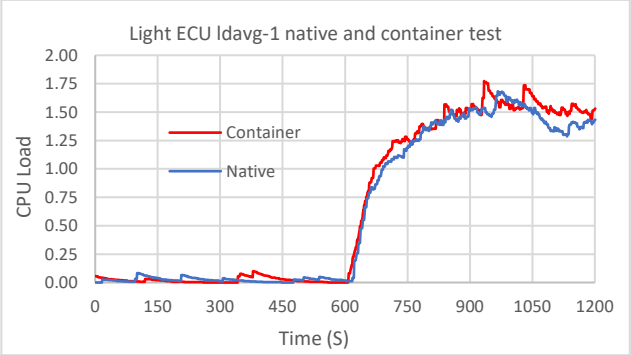


Chart 19: Light ECU *ldavg*-1 test

ldavg-1				
Light ECU	Min	Max	Execution Integration	Diff.
Native	0.0	1.68	775.50	
Container	0.0	1.77	818.01	42.51
Difference				+5.48%

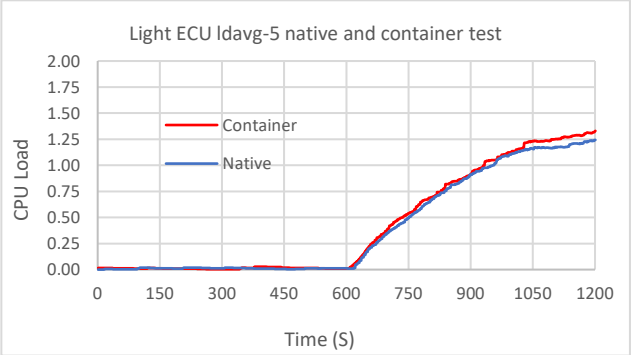


Chart 20: Light ECU *ldavg*-5 test

ldavg-5				
Light ECU	Min	Max	Execution Integration	Diff.
Native	0.57	1.01	497.95	
Container	0.02	1.33	514.95	17.00
Difference				+3.41%

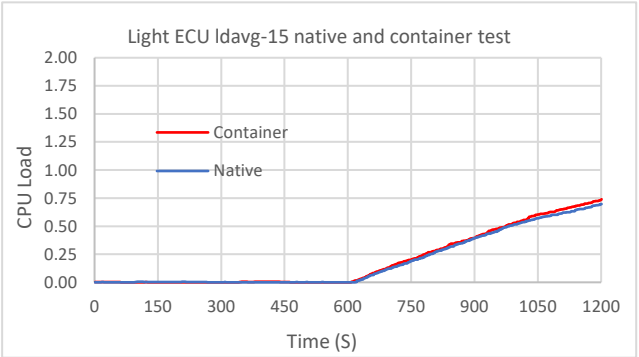


Chart 21: Light ECU *ldavg*-15 test

ldavg-15				
Light ECU	Min	Max	Execution Integration	Diff.
Native	0.23	0.83	232.65	
Container	0	0.74	236.83	4.18
Difference				+1.80%

6.7.5 CPU load average test summary

The baseline load average across all four ECUs was very low. A sample ECU was used to demonstrate the baseline *ldavg*-1, 5 and 15. All experienced a minimum load of zero for extended periods with a *ldavg*-1 peaking periodically at 0.17 (17%). The *ldavg*-5 and 15 results were lower than expected at 0.11 (11%) and 0.05 (5%) respectively. The average load across the entire base test run was 0.02 (2%). The *ldavg*-5/15 showed a decreasing trend over the test run, consistent with a CPU principally in an idle state.

For the native and container tests, the execution integration (area under the curve) results were obtained using the Trapezoidal rule. The difference between native and container test executions accurately display the additional CPU load required to support the container environment. During the native test mode, the load average across all three CPU load time frames was slightly elevated. Each ECU *ldavg* were very similar in load output. From execution, the *ldavg*-1 rose and levelled out at approximately 200 seconds from initial software execution. The *ldavg*-5 and 15 metrics saw gradual rises which were anticipated behaviour of a system under some load.

Total observed function load is the combination of all the ECUs *ldavg*. This observed figure shows total CPU load exhibited by the entire automotive function rather than individual ECUs. Table 6 below details the native *ldavg* triplets total integration values for the observed activity during the test run across all ECUs. The engine and Door ECU exhibited similar CPU loads with the gear and Light ECU displaying the highest and lowest CPU load average levels.

Native All ECU *ldavg* 1, 5 and 15 averages (4 Cores)				
ldavg-n	Engine	Gear	Door	Light
ldavg-1	772.73	802.64	775.50	683.00
ldavg-5	491.82	509.17	497.95	429.20
ldavg-15	230.19	239.38	232.65	200.96

Table 6: All native ECU load averages

A comparable increase in the *ldavg*-1, 5 and 15 load values across all four ECUs was observed during the container test mode. The native *ldavg*-1 metric during the container CPU load test levelled out at approximately 200 seconds after software execution. Table 7 details the native *ldavg* triplets total integration values across all ECUs.

Container All ECU *ldavg* 1, 5 and 15 averages (4 Cores)				
ldavg-n	Engine	Gear	Door	Light
ldavg-1	849.93	882.44	818.01	722.48
ldavg-5	535.23	509.17	514.95	451.97
ldavg-15	247.45	259.34	236.83	211.54

Table 7: All container ECU load averages

Again, the Gear ECU yielded the highest increase in CPU load. This particular ECU utilises three threads – two of which repeatedly send User Datagram Protocol (UDP) network traffic to the engine and Door ECUs to complete their functionality. The third thread receives data regarding the current gear selection from the Gear ECU. All three threads are continually active, which would account for the observed increase in CPU load on this ECU compared with the engine, door and Light ECUs. In a comparison between native and container tests, the additional load placed upon the system was minimal. Table 8 below displays the total CPU load required to support the entire automotive function across all four ECUs.

All ECU *ldavg* 1, 5 and 15 (Automotive Function Load)			
ldavg-n	Test Mode		Increase in CPU Load
	Native	Container	
ldavg-1	747.22	818.22	+9.50%
ldavg-5	482.04	502.83	+4.33%
ldavg-15	225.80	234.79	+3.98%

Table 8: All ECU total function load

When run within a container, the automotive function increases CPU load by nearly 10% during the *ldavg*-1 test - the increasing CPU loads over the *ldavg*-5 and 15 are approximately half the observed *ldavg*-1 CPU load. For individual ECU load average test results see Appendix C.

6.7.6 Scheduler statistics

The process scheduler is a core component of the OS kernel and decides how tasks run on the available CPU resources. Suppose there are more runnable processes than there are processors or processor cores. In this case, the scheduler must decide which process will run and which will be temporarily suspended and subsequently placed in a queue (*runqueue*). Enforcing process suspension is accomplished through pre-emptive multitasking. Upon creation, each process is provided with a portion of execution time known as a time slice, representing the amount of processor time allocated to that particular process. Two crucial metrics monitored for this research were:

- Time spent on CPU.
- Time spent waiting on *runqueue.*

All reported times are measured in nanoseconds (ns/10^{-9}) and converted to seconds and milliseconds, as observed in Table 9.

	Native ECU Mode				Container ECU Mode			
	Door	Engine	Gear	Light	Door	Engine	Gear	Light
Time on CPU	0.124s	0.146s	0.269s	0.124s	0.134s	0.196s	0.255s	0.121s
Wait on runq	0.052ms	0.062ms	0.115ms	0.041ms	0.018ms	0.032ms	0.047ms	0.011ms

Table 9: Scheduler statistics - time spent on CPU and *runq*

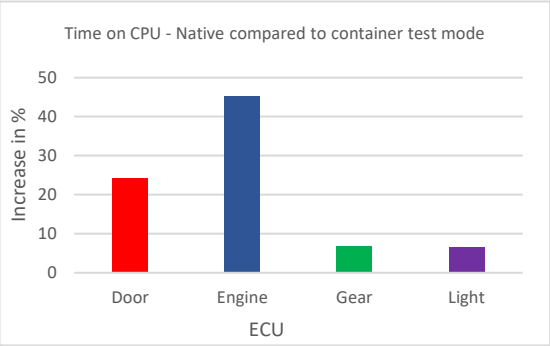


Chart 22: Time on CPU native and container test

Time on CPU	Native and Container ECU Mode			
	Door	Engine	Gear	Light
Native	0.124s	0.146s	0.269s	0.124s
Container	0.145s	0.212s	0.287s	0.132s
Difference	+24.19%	+45.26	+6.69%	+6.45%

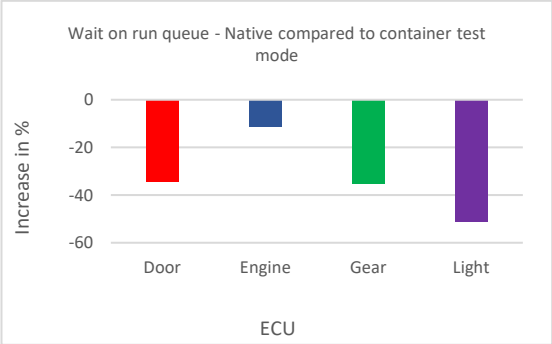


Chart 23: Time on run queue native and container test

Wait on Run Queue	Native and Container ECU Mode			
	Door	Engine	Gear	Light
Native	0.052ms	0.062ms	0.115ms	0.041ms
Container	0.034ms	0.055ms	0.085ms	0.020ms
Difference	-34.62%	-11.29%	-35.29%	-51.22%

During the container test mode, the software spent more time in execution than when in native test mode. In native test mode, the functional software spent a long time on the *runqueue* compared with the container test. As is standard in container operation, the software reserves an amount of CPU time specifically for execution. To replicate this effect during native execution, the native process priority level must be elevated to enable the native task more time on the CPU, which can have a detrimental impact on other processes running on the same system.

6.7.7 Task scheduling and system workload performance analysis

This test investigates the performance latency associated with the task scheduling of the system workload. The results presented in Charts 24 – 26 below represent a snapshot of each ECU in execution, in both native and container test modes. The *perf* tool collects large data sets relating to task scheduling and system workload. High sample rates caused CPU and I/O overloads which corrupted the sample data. Over a 5-second time frame, with the ECU in an idle state, 500 samples were collected, producing a report file size of 0.238MB. In contrast, an ECU in execution resulted in 731,286 samples producing a report file size of 79.647MB. Due to the high volume of scheduler related data collected over a relatively short period when the tool is in execution, it was decided that a 5-second data sample would be sufficient.

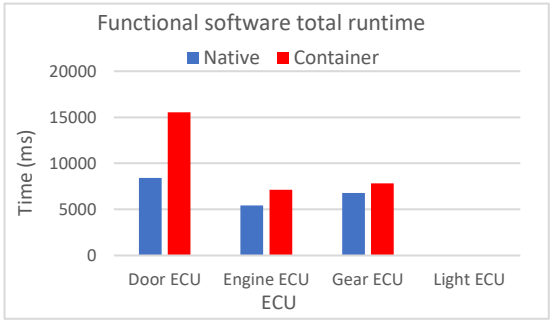


Chart 24: Functional software total runtime

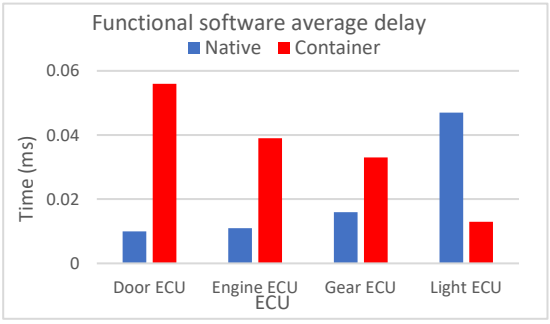


Chart 25: Functional software average delay time

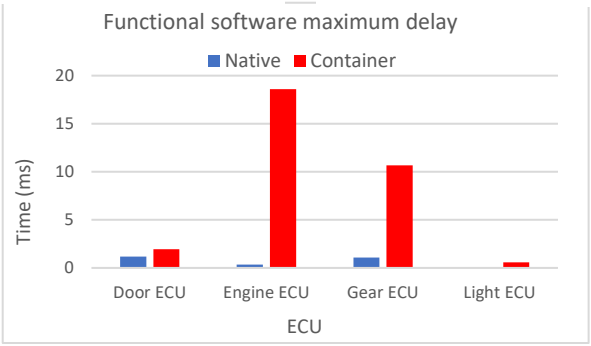


Chart 26: Functional software maximum delay time

5 second Sample	Native Test Mode (ECU Functional Software)			Container Test Mode (ECU Functional Software including shim)		
	Total Runtime (ms)	Average Delay (ms)	Maximum Delay (ms)	Total Runtime (ms)	Average Delay (ms)	Maximum Delay (ms)
Door ECU	8426.33	0.010	1.186	15549.91	0.056	1.93
Engine ECU	5442.862	0.011	0.354	7122.04	0.039	18.59
Gear ECU	6790.42	0.016	1.091	7843.49	0.033	10.67
Light ECU	4.40	0.047	0.062	7.41	0.013	0.58

Table 10: Native test ECU functional software timings

6.7.8 CPU saturation test summary

There were three primary metrics involved in measuring overall CPU saturation during the three test modes: *runq-sz, plist-sz* and *ldavg*. The *runq-sz* is a snapshot in time and represents the number of processes in memory which are waiting for CPU time to run. A consistently high *runq-sz* indicates that the CPU cannot service all processes requesting CPU time and therefore places the CPU in a state of saturation. Overall, the *runq-sz* test results revealed little variance in the number of waiting tasks between the ECU software running natively and a container implementation. The base test exhibited very little activity when the system was idle with only the OS in execution. Across the entire 1200 second test time frame, the observed *runq-sz* was predominately zero, with minor brief period fluctuations of between 1–2 waiting tasks. The number of running processes within the *runq-sz* did not increase significantly during either the native or container test modes. The overall average increase across all ECUs with the system in execution in container test mode was 43.55% higher than in comparison with the native test mode *runq-sz* average. However, this percentage equated, on average, to a single additional process/task but during both native and container tests, it was the Gear ECU that produced additional workload above the average of 43.55%, with peaks observed at 3–4 waiting tasks. Nevertheless, these additional waiting tasks were anticipated because of the heavy workload of this particular ECU. All other ECU increases were within the container *runq-sz* average. This specific test showed very little increase compared with native execution in the number of processes waiting in memory for CPU time when the automotive function executes within containers.

The *plist-sz* tests involved measuring the number of processes in memory and in execution. The more processes that are on this queue, the more CPU time and scheduler activity is required, both of which can have an overall detrimental effect on system performance. The base test run presented the current level of processes for the process queue whilst the system was idle. Although all ECUs were identical in hardware architecture, the software builds for each were different to reflect individual ECU functionality. During the native test mode, the average increase in the number of processes on the process list across all ECUs was observed at 135, representing an overall increase of 2.64% compared with the base test mode. The minimum recorded *plist-sz* increase was 0.7%, with the highest observed at 5.26%. The average measured increase in the *plist-sz* during the container test across all ECUs was 151 processes on the process queue, which equated to a rise of 12.41%. The minimum container test *plist-sz* increase was 9.09% with a maximum of 15.83%. The ECUs producing the highest *plist-sz* increases were the light and Door ECUs. These results differed from the previous *runq-sz* tests, where the Gear ECU exhibited the highest waiting task levels. The *runq-sz* averages for the Light and Door ECUs were higher than the Gear ECU because of the minimum recorded process list values, which artificially elevated their overall averages. However, they both exhibited the lowest *plist-sz* maximum, which was expected.

Compared to the *plist-sz* and *runq-sz*, the *ldavg* is not a snapshot in time and provides CPU load over a period of predefined time frames. The *ldavg* base test was extremely low, with a load average across all triplets of 0.02. All ECU hardware incorporated a quad-core processor which, at 100% CPU load equated to a value of 4.0. The *ldavg* value is the number of processes running and in an uninterruptable sleep mode. A *ldavg* value above 4.0 is considered as CPU oversaturation and the highest recorded loads across all of the *ldavg* triplets were observed on the *ldavg*-1 triplet of the Gear ECU which was observed at 2.28. However, this was a brief spike in CPU load rather than prolonged. The Gear ECU *ldavg*-1 value was as expected due to the higher workload for this particular ECU. The lowest observed triplet values recorded were from the Light ECU; again, these results were consistent compared with other test results. None of the native or container test results exhibited an excessive loaded system or an increasing load over any of the *ldavg* triplets. When comparing the CPU load results of both native and container tests, the results showed a slightly elevated CPU load when an ECU operated under the container system state.

The increase in overall CPU saturation when all the ECUs were executing within containers did not create excessive numbers of new tasks/processes nor did it add large numbers of processes on the process list or place an unreasonable or a disproportionate load on the CPU. Notably, with the automotive function in container operation, the average overall CPU load across all ECUs was 9.44% higher than with native execution mode. These tests demonstrate that CPU saturation did not occur on any individual ECU whilst the automotive function executed within a container environment.

6.8 CPU Utilisation Tests

CPU saturation refers to the amount of work or load that is waiting to be serviced, whereas CPU utilisation is the measurement of the requirement divided by the capacity. High CPU utilisation can indicate poor application performance where processes must remain in the processor queue for other processes to complete execution. The principle CPU metrics monitored during these series of tests were:

- %user - percentage of CPU utilisation while executing processes at the application (user) level.
- %system - percentage of CPU utilisation while running processes at the system (kernel) level.
- %idle - percentage of time the CPU was inactive with no outstanding disk I/O requests.
- %nice - percentage of CPU utilisation executing higher-level processes at the user level.
- %iowait - percentage of time the CPU was idle with outstanding disk I/O requests.

The %user pertains to kernel activities such as servicing interrupts and resource management. The %user metric measures the amount of CPU used to run user applications such as command shell, compiler and software code. %user space programs and processes are subdivided under priority levels known as a *nice* priority or value. The %nice value must also be considered when examining overall CPU utilisation - a positive value indicates higher priority user-level processes which can affect overall CPU utilisation. A system that exhibits high CPU utilisation levels with a relatively low %nice level can indicate that the processor is servicing an increased number of processes that can ultimately degrade system performance.

The *nice* value for any process was not altered during the ECU resource tests. However, it was necessary to manipulate the *nice* value for executing processes during the container suitability tests, which is explained

in further detail in Section 6.12.13 of this chapter. If the %user + %nice + %system total is equal to 100% CPU utilisation, then the workload is considered CPU bound. A constant or long-term high level of CPU utilisation can result in several adverse factors, including:

- High temperatures can reduce the CPU's operational lifetime or can cause premature failure.
- An increase in overall power consumption (an essential factor in automotive systems).
- A subsequent increase in CPU utilisation.

The modelled ECUs each utilised a quad-core processor and during both native and container system tests, 100% CPU utilisation occurred at 400%. In understanding the overall picture of CPU utilisation, it was necessary to measure the number of Instructions Per Cycle (IPC) achieved by the ECU system. This determined how efficient the functional software executed on the hardware and indicated if the workload was memory or processor bound.

6.8.1 %user, %system and average CPU utilisation

The output data from the monitoring tools *iostat, mpstat, vmstat* and *sar* all provided similar output results and were used to ensure data correctness and consistency across the modelled ECU CPU cores. The monitored metrics involved with these tools were %user, %system and % idle. The following base system test results show the individual %user and %system CPU utilisation and the combined total, which provides a total CPU utilisation across all four CPU cores.

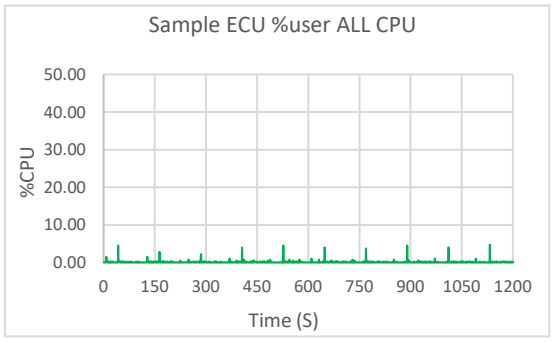


Chart 28: Sample %user across all CPUs

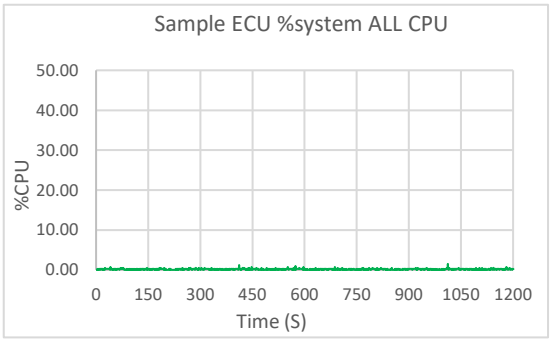


Chart 27: Sample %system across all CPUs

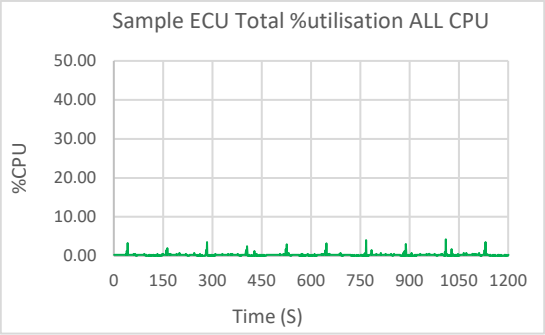


Chart 29: Sample %utilisation across all CPUs

Base CPU Utilisation			
Engine ECU	Min	Max	Average
%user	0%	4.76%	0.10%
%system	0%	1.51%	0.16%
%utilisation	0%	4.76%	0.26%

The %user metric shows slightly elevated activity when compared with the %system. The additional activity observed in the %user results was the combination of several user-initiated processes, including the monitoring tools used and the ssh and bash processes which enabled remote access to the ECU OS. In this case, the %system results show the actual system CPU utilisation in an idle state. The following charts (Charts 30 – 41) display the overall total CPU utilisation of each ECU in both native and container test modes. For individual ECU CPU utilisation tests, see Appendix D.

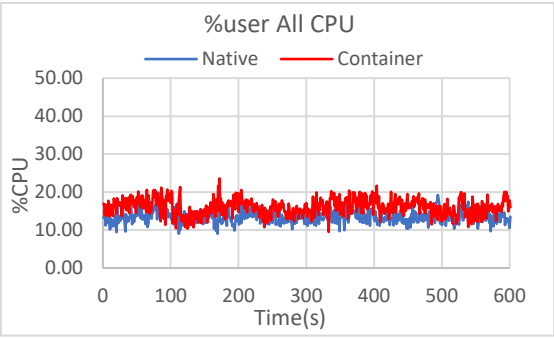


Chart 31: Engine ECU %user native and container test

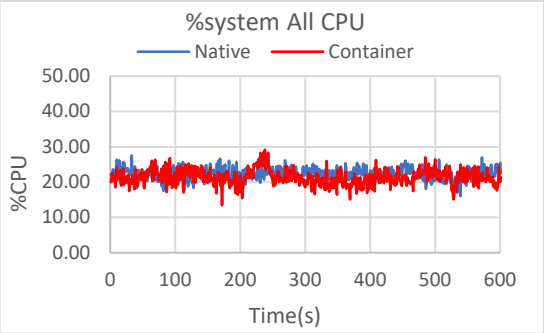


Chart 30: Engine ECU %system native and container test

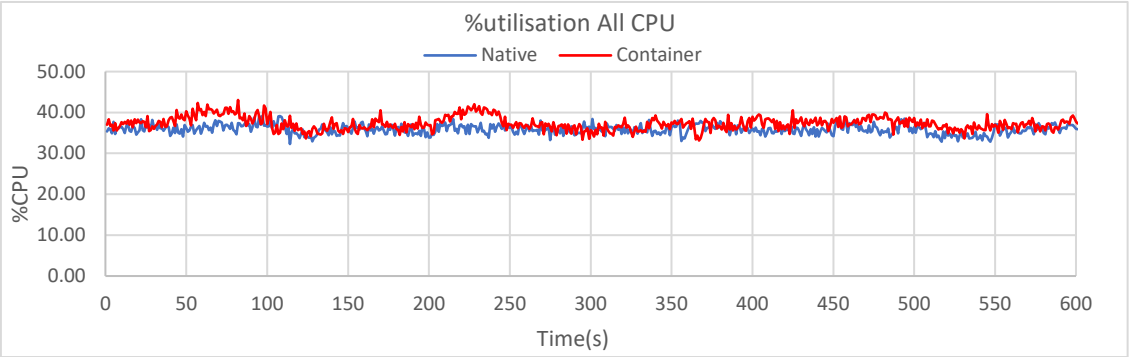


Chart 32: Engine ECU %utilisation native and container test

CPU Utilisation									
Engine ECU	%user			%system			%utilisation		
	Native	Container	Difference	Native	Container	Difference	Native	Container	Difference
Minimum	9.04%	9.50%	+5.09%	19.88%	23.58%	+18.61%	13.51%	16.06%	+18.87%
Maximum	16.01%	13.43%	-16.11%	27.54%	29.11%	+5.70%	22.41%	21.30%	-4.95%
Average	32.29%	33.14%	+2.63%	39.19%	43.05%	+9.85%	35.91%	37.37%	+4.07%

Table 11: Engine ECU CPU utilisation data

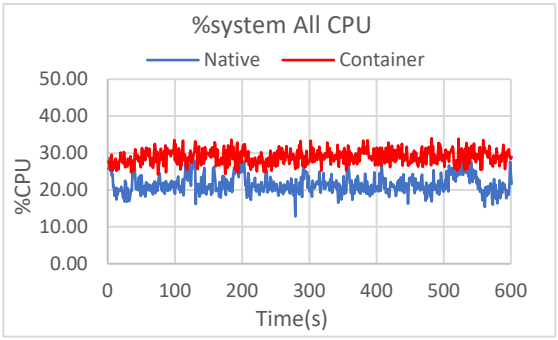


Chart 34: Gear ECU %system native and container test

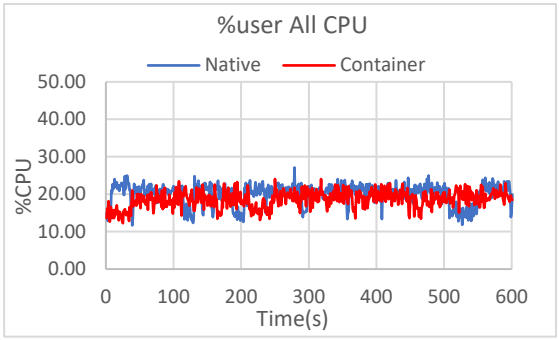


Chart 33: Gear ECU %user native and container test

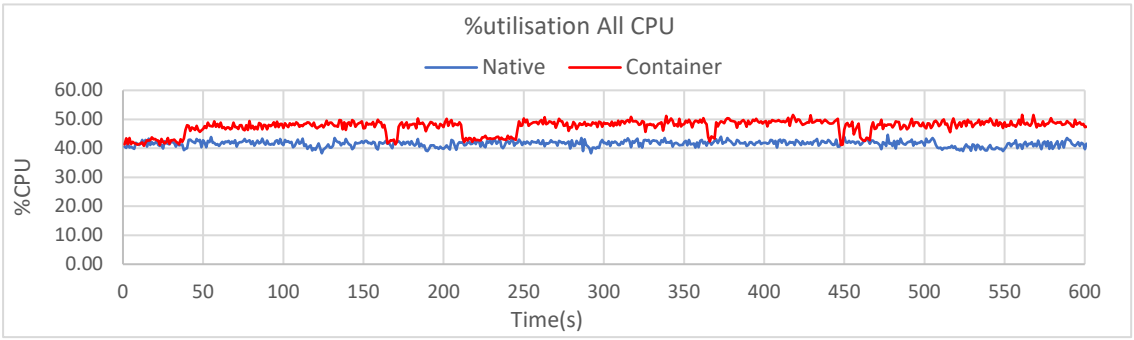


Chart 35: Gear ECU %utilisation native and container test

CPU Utilisation									
Gear ECU	%user			%system			%utilisation		
	Native	Container	Difference	Native	Container	Difference	Native	Container	Difference
Minimum	11.65%	12.24%	+5.06%	27.11%	+24.05%	-11.29%	20.11%	18.60%	-7.51%
Maximum	12.83%	24.17%	+88.38%	28.81%	+34.01%	18.05%	21.54%	29.01%	+34.68%
Average	38.28%	40.85%	+6.71%	44.66%	+51.55%	+15.43%	41.66%	47.61%	+14.28%

Table 12: Gear ECU CPU utilisation data

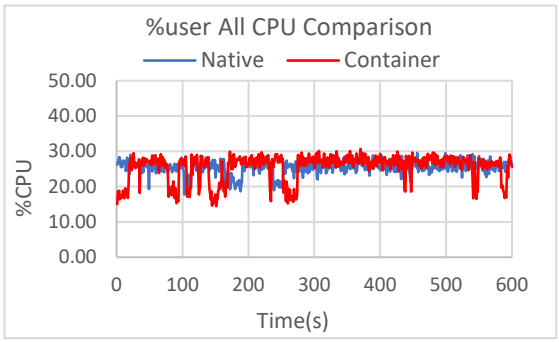


Chart 36: Door ECU %user native and container test

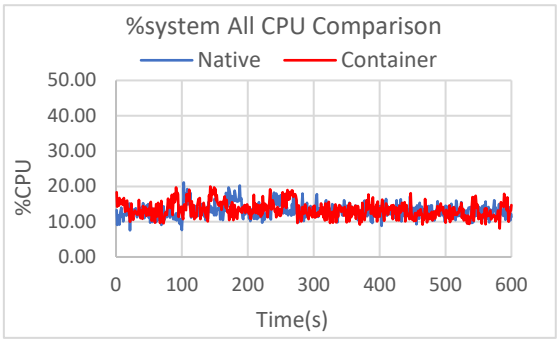


Chart 37: Door ECU %system native and container test

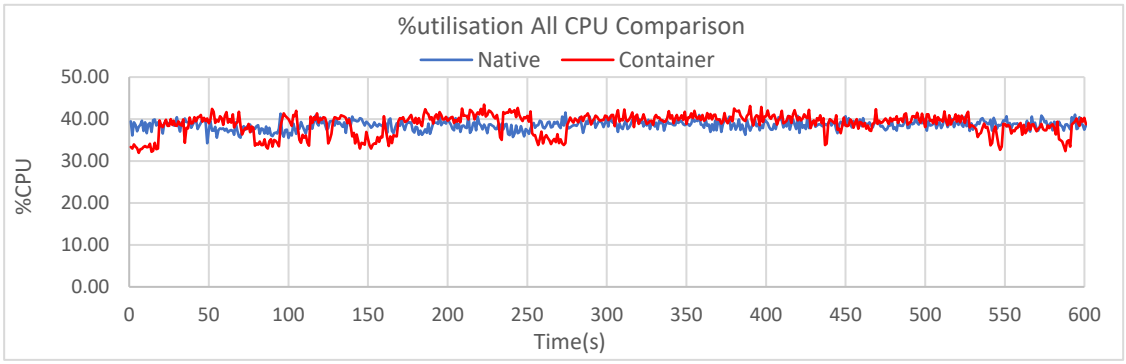


Chart 38: Door ECU %utilisation native and container test

CPU Utilisation									
Door ECU	%user			%system			%utilisation		
	Native	Container	Difference	Native	Container	Difference	Native	Container	Difference
Minimum	14.45%	17.81%	+18.87%	29.57%	30.67%	+3.72%	25.46%	25.49%	+0.12%
Maximum	7.55%	8.07%	+6.89%	21.10%	19.95%	-5.45%	13.16%	13.36%	+1.52%
Average	31.94%	34.24%	+6.72%	41.55%	43.44%	+4.55%	38.62%	38.85%	+0.60%

Table 13: Door ECU CPU utilisation data

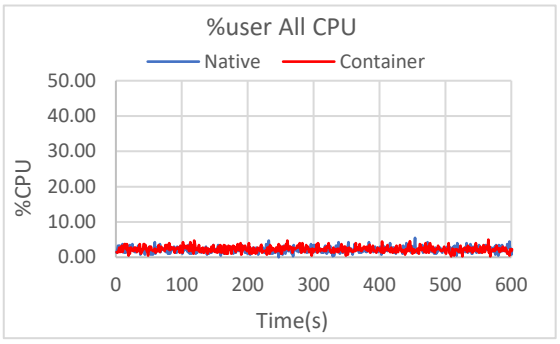


Chart 39: Light ECU %user native and container test

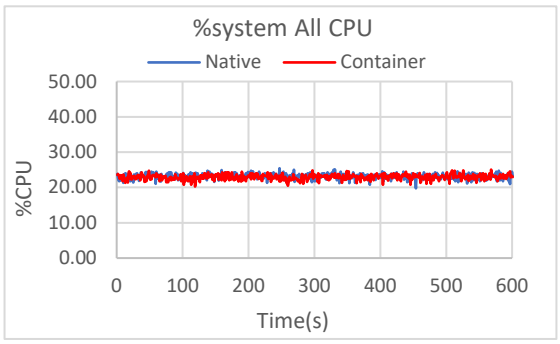


Chart 40: Light ECU %system native and container test

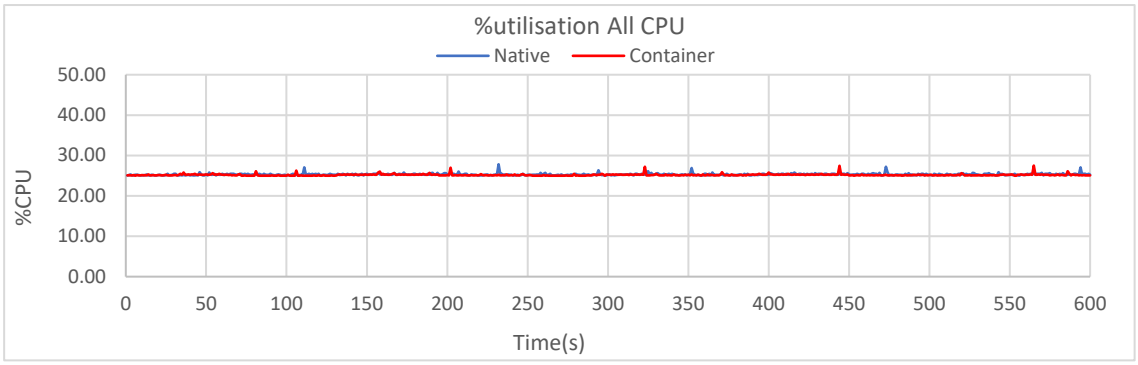


Chart 41: Light ECU %utilisation native and container test

CPU Utilisation									
Light ECU	%user			%system			%utilisation		
	Native	Container	Difference	Native	Container	Difference	Native	Container	Difference
Minimum	0.25%	0.75%	+200%	5.0%	+5.50%	10.0%	2.27%	2.14%	-5.73%
Maximum	20.25%	19.75%	-2.47%	25.06%	+25.44%	1.51%	22.96%	23.20%	+1.05%
Average	25.00%	25.00%	0%	27.50%	+27.82%	1.16%	25.23%	25.35%	+0.48%

Table 14: Light ECU CPU utilisation data

6.8.1 CPU Utilisation Summary

Similar to CPU saturation baseline, tests exhibited minimal amounts of recorded overall CPU utilisation. The average baseline CPU utilisation across all ECUs was 0.02%. However, the monitoring tool that was used determined the overall metric output. For example, the monitoring tools top and htop showed a %CPU value for utilisation. This value represents the sum of all CPU cores. The total %CPU use reported in a four-core CPU totalled 400% which equates to 100% system CPU utilisation. The output results from the utilisation tests represent CPU utilisation and in a four-core system, where 100% utilisation is measured across all four cores. The overall utilisation measured for these tests constituted the sum of %user (application) and %system (kernel). Table 15 below represents the averages of %user, %system and %utilisation across all four ECUs.

Average CPU Utilisation									
ECU	%user			%system			%utilisation		
	Native	Container	Difference	Native	Container	Difference	Native	Container	Difference
Engine	32.29%	33.14%	+2.63%	39.19%	43.05%	+9.85%	35.91%	37.37%	+4.07%
Gear	38.28%	40.85%	+6.71%	44.66%	+51.55%	+15.43%	41.66%	47.61%	+14.28%
Door	31.94%	34.24%	+6.72%	41.55%	43.44%	+4.55%	38.62%	38.85%	+0.60%
Light	25.00%	25.00%	0%	27.50%	+27.82%	1.16%	25.23%	25.35%	+0.48%

Table 15: All ECU CPU utilisation data

The Gear ECU exhibited the highest recorded percentages during both the native and container test modes where total CPU utilisation was 41.66% and 47.61% respectively. The lowest was the Light ECU where native and container CPU utilisation experienced very similar levels of 25.23% and 25.35%. %user CPU utilisation represents the ECU functional script in execution. The %user average increase was measured at +5.25% when the script executed within the container. The %system utilisation container results show the additional required processes/tasks needed to support the container. These additions include the container shim, docker and *containerd* processes. The container %system utilisation represented an overall average system function increase of 7.75%. The total additional %user and %system required to support the entire modelled central locking system was 13.0% compared with the native mode of operation. The 13.0% figure

is relatively low, however, the Gear ECU has already been highlighted as a highly utilised ECU due to its critical function within the modelled central locking mechanism.

6.8.2 Instructions per cycle

IPC measure how many instructions are completed during each CPU clock cycle. The modelled ECUs used for this research incorporate a quad-core ARM Cortex-A53 processor. The stated IPC value for the ARM Cortex-A53 processor is 2.0. This IPC value represents the total number of instructions that the CPU can be executed per clock cycle. The ARM Cortex-A53 IPC value was used as a benchmark during the three test modes to provide an overall value in understanding CPU utilisation concerning IPC. The IPC test results obtained can be observed in Chart 42.

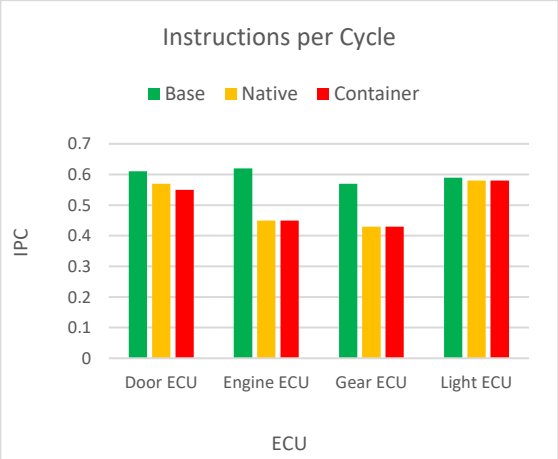


Chart 42: Instructions per cycle - all ECUs, all tests

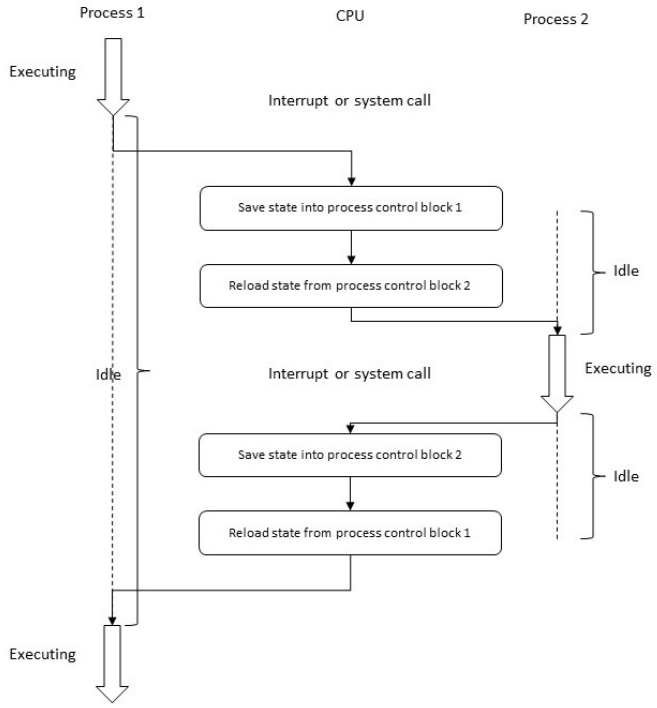
60 second Sample	Instructions Per Cycle (IPC)			
	Base	Native	Container	%diff
Door ECU	0.61	0.57	0.55	-3.50
Engine ECU	0.62	0.45	0.45	0.00
Gear ECU	0.57	0.43	0.43	0.00
Light ECU	0.59	0.58	0.58	0.00

6.8.3 Instruction per cycle test summary

As the load on the CPU increases, it affects the overall IPC value. The maximum stated Cortex-A53 CPU IPC value is documented at 2.0. However, when recorded during the base operation test mode, the base level IPC value was between 0.57 and 0.62 across all four modelled ECUs. The results obtained from the native and container test modes revealed that there was very little difference between the two test mode IPC values. The Door ECU showed a slight decrease in the IPC value of -3.50% when executing within the container. The results of this particular test highlight that regardless of ECU functional operation mode, there was little to no drop in the number of instructions per second executed on the ECU processor.

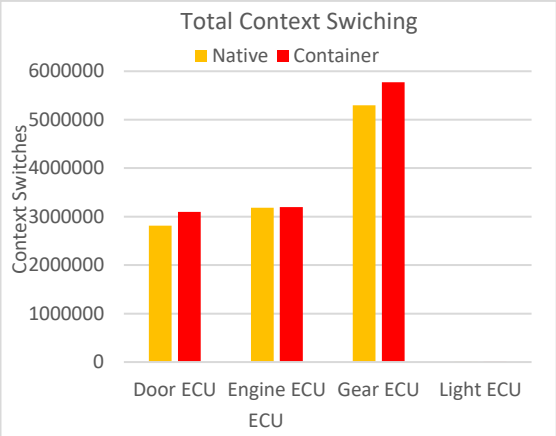
6.8.4 Context switching (*sar -w* & *vmstat* & *perf stat*)

A context switch is a mechanism of storing an old process or thread state so it can be restored and execution resumed at a later time, whilst loading the next process state. The time between the save and reload states of each process has a cost in system performance. Excessive context switching can affect system performance and a negative impact on CPU utilisation. Context switching involves switching registers, stack pointer, program counter, flushing memory cache and loading the process page table within the Linux kernel. During this period, the CPU is idle from the user perspective. Figure 34 illustrates the procedure of context switching between two processes.



1. Process 2 is in a ready state awaiting execution
2. An interrupt or system call forces process 1 to save state in process control block 1 (PCB1)
3. PCB1 is moved to relevant I/O, wait or ready queue
4. PCB2 sets process 2 to running state from position of last executed instruction
5. Process 1 is in a ready state awaiting execution
6. An interrupt or system call forces process 2 to save state in PCB2
7. PCB2 is moved to relevant I/O, wait or ready queue

Figure 35: Context switching process



60 second Sample	Total Context Switching			
	Base	Native	Container	%Diff
Door ECU	3289	2814007	3100505	+10.18%
Engine ECU	3628	3181499	3195296	+0.43%
Gear ECU	3975	5296767	5771266	+8.96%
Light ECU	2864	3924	4390	+11.87%

Chart 43: Native and container context switching across all ECUs

6.8.5 Context switching

The Gear ECU exhibited high overall context switching levels, which was consistent with the high level of work placed upon this ECU. The Light ECU has a minimal function within the central locking system. This was reflected in the very low level of context switching observed during both native and container tests. The overall increase in context switching experienced across all four ECUs was an average of +7.86% with a low of +0.86% and a high of 11.87%.

6.9 Memory Saturation

This section investigates memory saturation, which determines how much data is written to and read from the main system memory during ECU operation. Memory saturation is an essential factor in overall system memory management. When available system memory is close to being exhausted, the system will start to free memory from the buffers and caches as well as initiate the swapping process. As the number of pages entering and exiting memory increases, it will have a detrimental effect on overall system performance. Primary indications of memory saturation are scan rate and swap activity.

6.9.1 Memory scan rate

The scan rate is defined as the reclamation of memory when available memory falls below a certain threshold. The page scanner process identifies in memory which pages are no longer required and subsequently places them on the free list. A key indicator in determining whether the system is running out of available physical memory is the page scanning rate. If the page scan rate is above zero for an extended period, it can suggest the system is running low on physical memory. Brief spikes in scan rate activity may result from transient issues of the recently started process reading large amounts of uncached data. To ensure that any momentary problems are eliminated, the following memory tests were run for an extended time frame and sampled data taken from a specified time point within each test. When a new process starts, memory is allocated to that process. The following memory saturation tests investigate how much memory is assigned to each process, including the number of unused reclaimed memory, buffer and cache pages. These test results link to the page scanner process that indicates how aggressive the page scanner must be to keep up with system memory demands. In regular operation, up to 4% of CPU time is allocated to the memory reclamation process. When demand is excessively high, this can rise to 80% of CPU time depending upon the amount of available memory and the initialisation of new processes. The following Charts 45 - 55 show the comparison between the *frmpg/s*, *bufpg/s* and *campg/s* across both native and container test modes. The ECU functional software initialised at 60 seconds into the test.

Frame memory pages (*frmpg/s)* – number of memory pages freed by the system per second. A positive value relates to the number of memory pages released for future use. A negative value indicates the number of memory pages allocated.

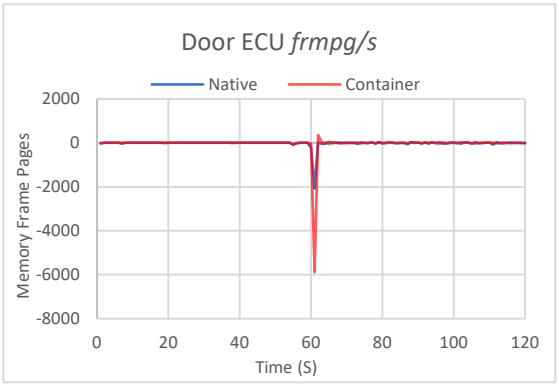


Chart 45: Door ECU *frmpg*/s native and container test

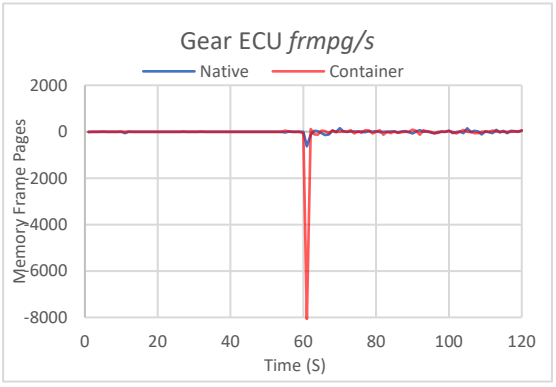


Chart 44: Gear ECU *frmpg/s* native and container test

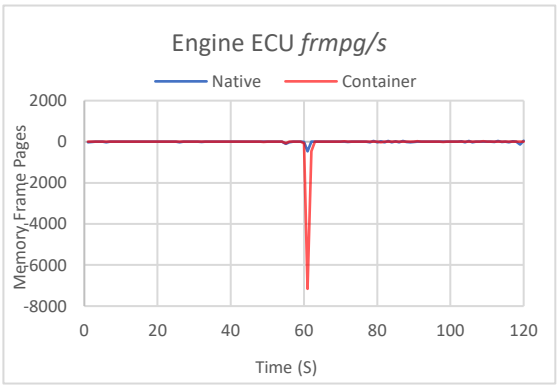


Chart 47: Engine ECU *frmpg/s* native and container test

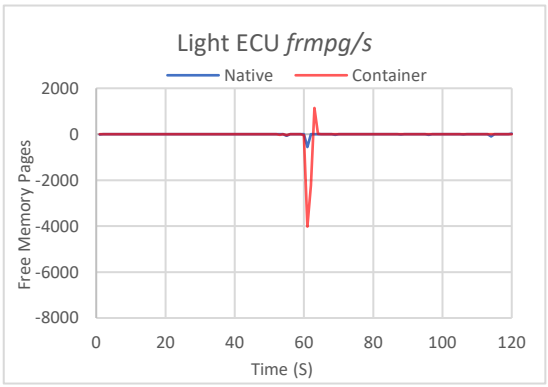


Chart 46: Light ECU *frmpg/s* native and container test

6.9.1.1 Memory buffers allocated

Memory buffers (*bufpg/s*) – this value represents the number of memory pages allocated as buffers per second. A negative value indicates the number of buffer pages released back to the system.

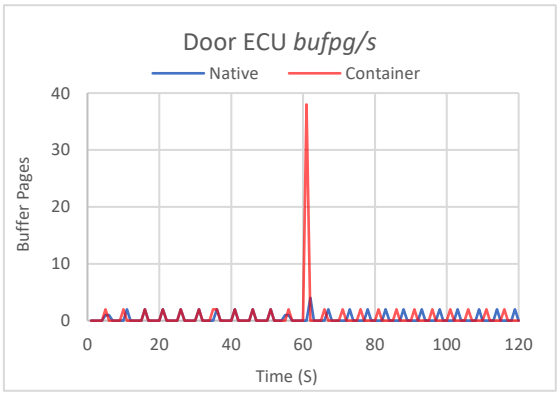


Chart 48: Door ECU buffers allocated native and container test

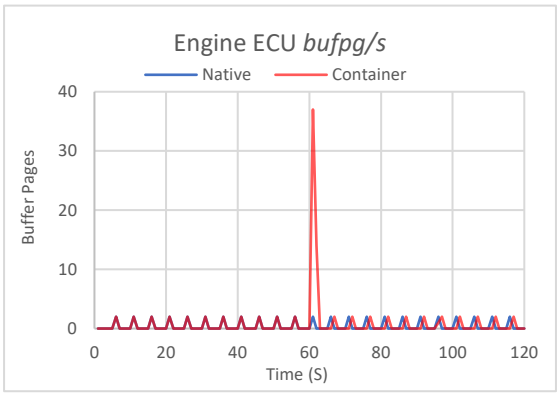


Chart 49: Engine ECU buffers allocated native and container test

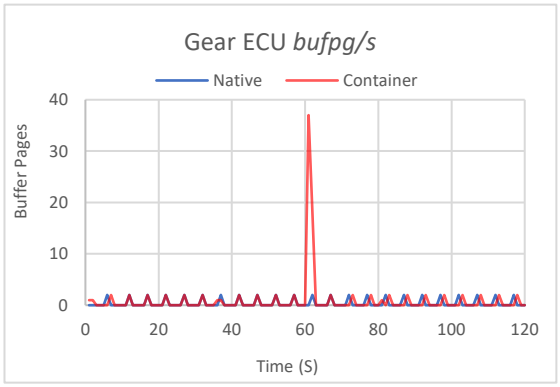


Chart 50: Gear ECU buffers allocated native and container test

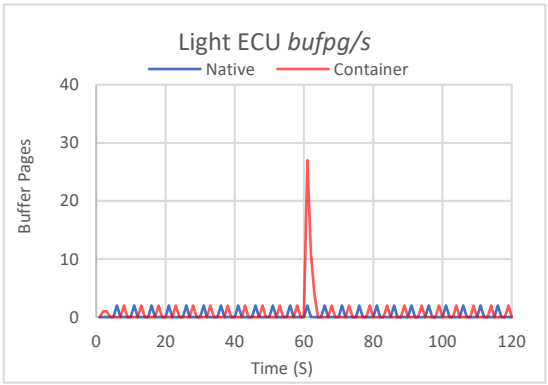


Chart 51: Light ECU buffers allocated native and container test

Memory cache pages (*campg/s*) – this value represents additional memory pages cached by the system. A negative amount represents pages released from the cache.

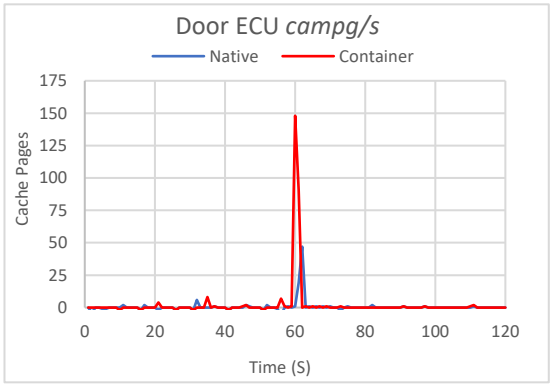


Chart 52: Door ECU cached pages native and container test

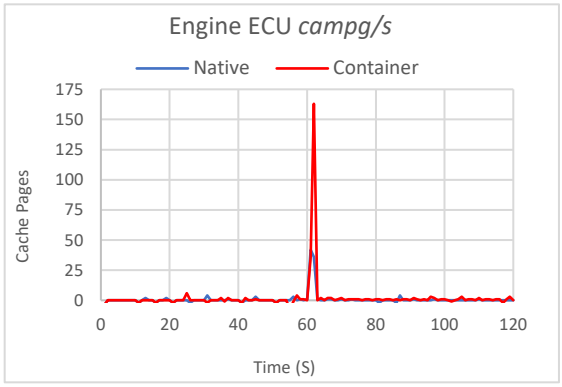


Chart 53: Engine ECU cached pages native and container test

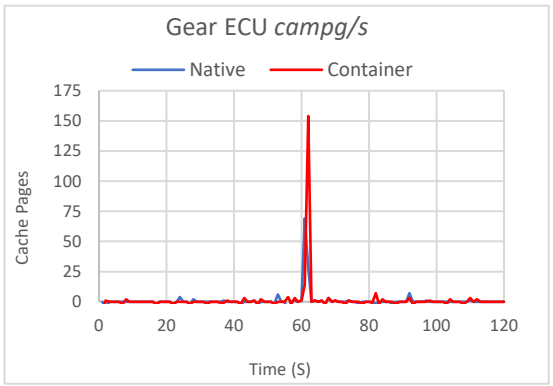


Chart 54: Gear ECU cached pages native and container test

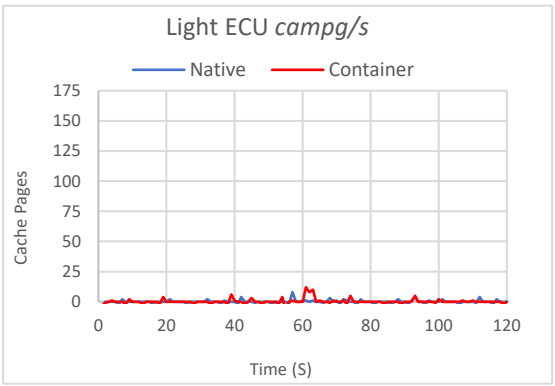


Chart 55: Light ECU cached pages native and container test

6.9.1.2 Memory scan rate summary

The system's free memory pages show how many pages have been released back to the system to accommodate the software execution. Allocated memory pages were only observed during the rest of the test run in native and container modes. The Gear ECU released the largest amount of memory back to the system and the Light ECU the least, which is consistent with the operation of these two ECUs. More memory is allocated at the initial execution of the container as observed in the *frmpg/s* metric. The results are consistent with the Light ECU exhibiting the smallest, and the Gear ECU the highest, allocation of memory. However, the increase in difference shows the Door ECU with the lowest increase. On investigation, this was due to higher memory levels used to invoke the native Door ECU software. The *bufpg/s* metric

represents the amount of memory required by the kernel to read information, which typically comes from secondary storage to keep operational speeds to an optimum when accessing data from relatively slower storage media types. The observed buffer allocation was periodic and low with a small observed spike in allocation when ECU software initialisation occurred with no other observed spikes in buffer page allocation. These results were consistent with little to no observed disk activity. The cache pages per second metric were again observed at a low value across native and container test modes. Three of the four ECUs had similar cache page allocation peaks of approximately 150 *campg/s* at script initialisation with little activity recorded during the duration of the test run. The difference in percentages between native and container test modes was high, especially within the *frmpg/s* metric, where the percentage difference was an average of +572%. The bufpg/s and campg/s increases are smaller at +99% and +182% respectively. Table 16 below is the summary of the associated individual component metrics of the memory scan rate test.

	Free Memory (pg/s)			Buffers (pg/s)			Cache (pg/s)		
	Native	Container	%diff	Native	Container	%diff	Native	Container	%diff
	Total	Total		Total	Total		Total	Total	
Door ECU	-2579	-5750	122.95	48	84	75.00	67	262	291.04
Gear ECU	-1002	-8373	735.63	46	102	121.74	98	169	72.44
Engine ECU	-818	-7706	842.18	46	96	108.70	87	238	173.56
Light ECU	-758	-5205	586.66	46	88	91.30	10	29	190.00

Table 16: Total free memory, buffers and cache

6.9.2 Memory swap activity

Another aspect of memory saturation is concerned with paging. When a system runs out of available physical memory, inactive memory pages swap from main memory to virtual memory which are usually stored temporarily on a secondary storage device. Paging delay for a given CPU utilisation is defined as:

$$PD = \frac{C}{1 - \mathrm{U}} * R * T \qquad 1.3$$

- PD = paging delay.
- C = CPU service time for a transaction.
- U = CPU utilisation (expressed as a decimal).
- R = paging out rate.
- T = service time for the swap device.

As paging increases, so does overall CPU utilisation. High rates of memory utilisation lead to slower memory read times. This may increase CPU utilisation due to an increased level of CPU interrupts required to manage the paging process. To maintain a responsive system, paging/swapping must be kept to a minimum, ideally zero. The paging rate of 10 per second would account for 5% of overall CPU utilisation - by increasing the paging rate to 20 per second would increase CPU utilisation by an additional 5%. Due to the modelled ECU architecture, it was anticipated that paging would not be an issue across any of the test modes but would still be observed.

Each ECU script is relatively small and the memory required to execute the script is minimal compared with the amount of available ECU system memory. There was no observed swap activity across all four ECUs in both native and container execution modes.

6.9.3 Page faults (major and minor)

Memory page faults are a routine procedure of loading executable files and data into memory as and when a new or current process requires more code. A minor (frame reclamation) fault is raised when a process requests data which has already been loaded into memory but not currently allocated to that particular process. They should remain at a constant level throughout. Chart 56 reveals the total number of page faults raised over a 60-second test for each individual ECU. Excessive minor page faults can lead to memory over-saturation and incur latency within the executing program. A major page fault (that requires an I/O operation) is raised when the ECU functional software is first loaded into memory, which can be observed in Chart 58 below. Major page faults are more of a concern as a new process requires data that the kernel must fetch from disk which takes longer due to the disparity between slower secondary storage and system memory speeds.

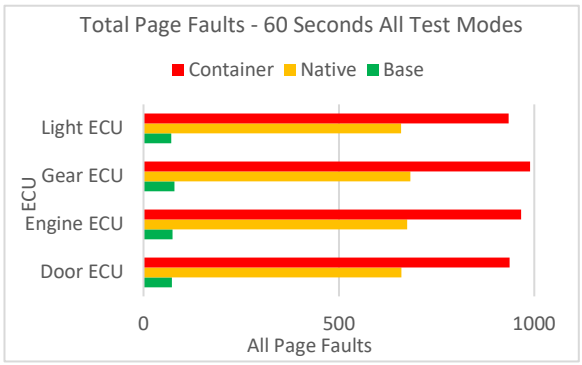


Chart 56: Total page faults - all ECUs, all test modes

60 second test	Total Page Faults - *perf*			
	Base	Native	Container	%diff
Light ECU	73	675	966	43.11
Gear ECU	79	660	989	49.85
Engine ECU	74	683	934	36.75
Door ECU	71	659	937	42.19

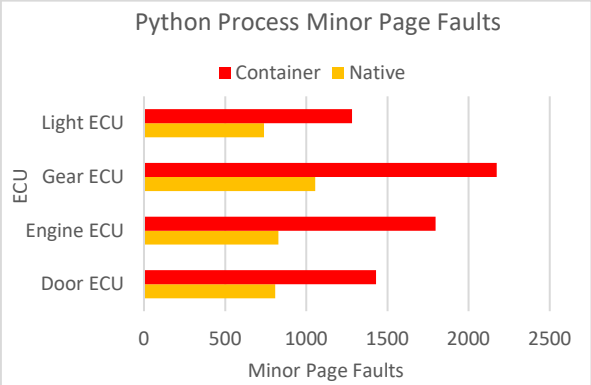


Chart 57: Minor page faults raised by python script - all ECUs

ps -eo	Python process specific page faults		
	Native	Container	%diff
	min_flt	min-flt	
Light ECU	739	1282	73.48
Gear ECU	1056	2173	105.78
Engine ECU	828	1796	116.91
Door ECU	808	1430	76.98

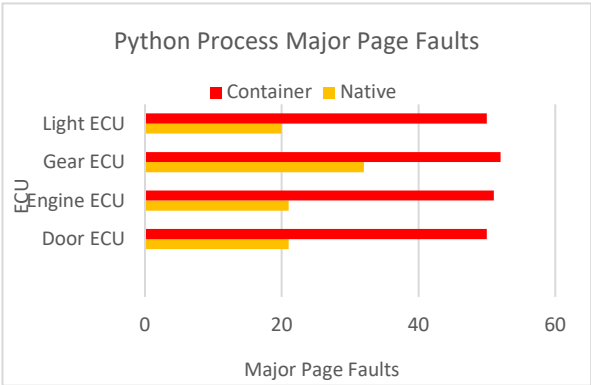


Chart 58: Major page faults raised by python script - all ECUs

Ps -eo min_flt,maj_flt	Python process specific page faults		
	Native	Container	%diff
	major	major	
Light ECU	20	50	150.00
Gear ECU	32	52	62.50
Engine ECU	21	51	142.86
Door ECU	21	50	138.09

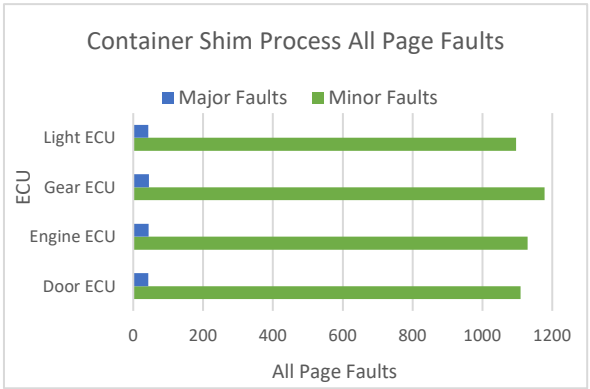


Chart 59: All page faults raised for *shim* execution

Ps -eo min_flt,maj_flt	Shim process	
	Container	
	Minor faults	Major faults
Light ECU	1096	43
Gear ECU	1178	45
Engine ECU	1129	44
Door ECU	1109	43

6.10 Memory Utilisation

Memory utilisation is the amount of system memory (RAM) used during software execution compared with free memory. CPU utilisation refers to the amount of CPU time, which consists primarily of the sum of %user and %system. Memory utilisation is the sum of memory used by all processes divided by the total available memory. When a new process executes, it is allocated a portion of available memory for the correct functioning of that process. If there is not enough available memory, the process cannot be created. The following tests were carried out to observe any differences in memory use and allocation between native and container test modes, as seen in Figures 60 – 63.

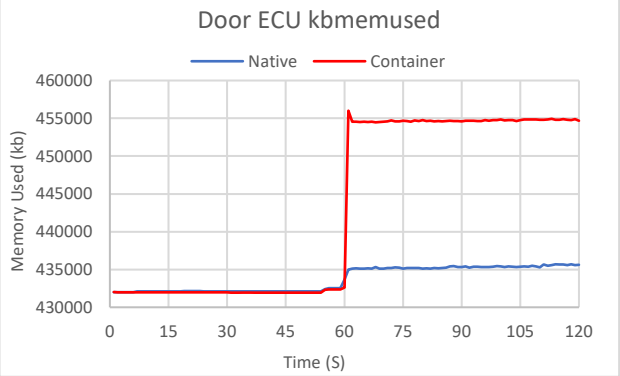


Chart 60: Door ECU memory use native and container test

Test Mode	Door ECU Memory Use		
	Average	Difference	%diff
Base	432000kb	-	-
Native	435688kb	3688kb	-
Container	456004kb	20316kb	+450.87

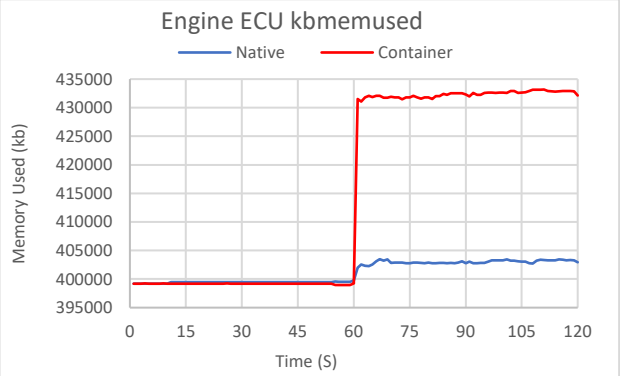


Chart 61: Engine ECU memory use native and container test

Test Mode	Engine ECU Memory Use		
	Average	Difference	%diff
Base	399192kb	-	-
Native	401203kb	2011kb	-
Container	415753kb	14550kb	+623.52

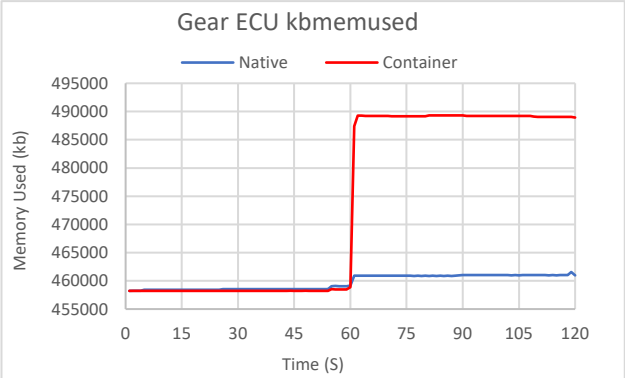


Chart 62: Gear ECU memory use native and container test

Test Mode	Gear ECU Memory Use		
	Average	Difference	%diff
Base	458224kb	-	-
Native	459742kb	1518kb	-
Container	473712kb	13970kb	+820.29

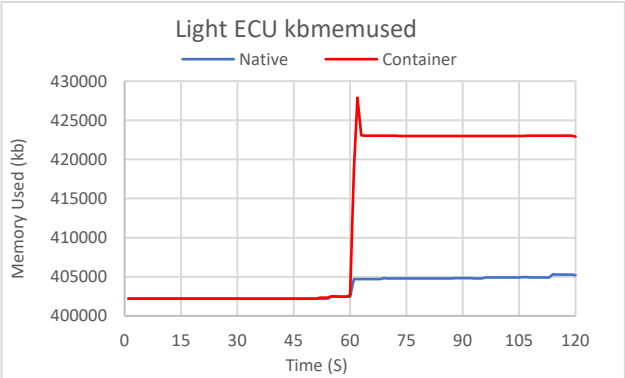


Chart 63: Light ECU memory use native and container test

Test Mode	Gear ECU Memory Use		
	Average	Difference	%diff
Base	402192kb	-	-
Native	403552kb	1360kb	-
Container	412625kb	9073kb	+567.13

6.10.1 Memory unique set size

Traditional memory monitoring tools focus on Resident Set Size (RSS). The RSS is the amount of physical memory occupied by a process. However, the RSS is often an overestimation of process memory use and shows little information on any memory pages shared between processes. The Proportional Set Size (PSS) details the amount of main memory allocated to a process, which includes memory allocated for the sole use of that process and the proportion of memory shared with other processes. It is essential to understand how much memory is being used proportionally and exclusively by comparing memory use between native and container test modes. The Unique Set Size (USS) is the amount of private, unshared memory allocated

solely to a specific process and is a true reflection of how much memory the kernel assigns to an individual process. During the native and container test modes, the used memory data is shown in Charts 65 and 66.

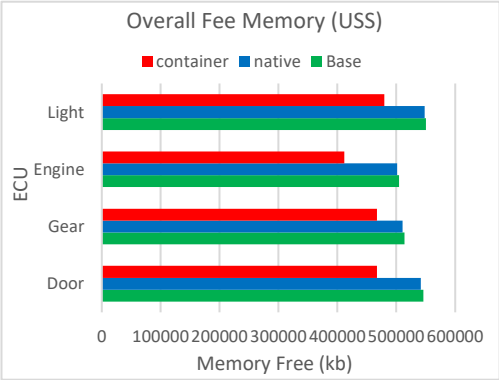


Chart 64: Unique set size memory - all ECUs, all tests

ECU	Total System Available Free Memory (kb)				
	Base	Native	Container	Diff	%
Door	546076	541464	467400	74064	+13.56
Gear	514048	510588	466884	43704	+8.50
Engine	504480	501556	411616	89940	+17.83
Light	550488	547932	479688	68244	+12.40

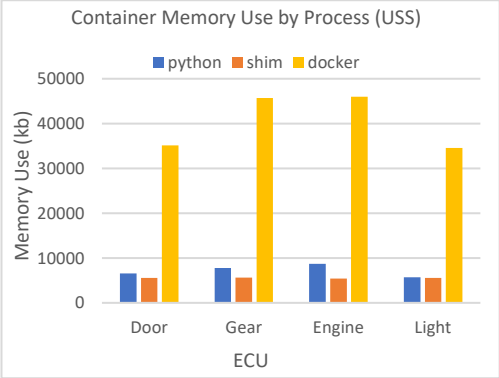


Chart 65: Unique set size by process container test

ECU	Total Container Memory Use (kb)		
	python	shim	docker
Door	6596	5588	35128
Gear	7772	5624	45704
Engine	8688	5428	45960
Light	5724	5592	34580

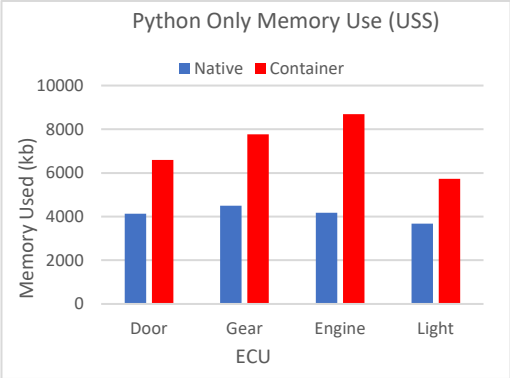


Chart 66: Unique set size python only - all ECUs, native and container test

ECU	Automotive Functional Software Memory Use (kb)			
	Native	Container	Diff	%diff
Door	4125	6596	2471	+59.90
Gear	4496	7772	3647	+81.12
Engine	4172	8688	4192	+100.48
Light	3676	5724	1552	+42.22

6.10.2 Memory utilisation and saturation summary

The *perf* stat tool captured a 60-second snapshot regarding the total page faults (minor and major) generated during each test mode. The base test mode, as expected, yielded a low level of page faults during the execution of just the OS. The container operational mode displayed an average increase of 42.98% compared with the native operation test, with a high of 49.85% and a low of 36.75%. During the native test mode, both major and minor page faults related to the functional script's execution. In contrast, additional page faults were observed due to additional services required to support the container ecosystem and the embedded python script. The *ps* command examined the specific minor and major page faults raised since python script execution and running the software tool. During a five-minute sample test run, the number of minor faults raised whilst executing the python script during the container test resulted in an average increase of 93.22% with a low of 73.48% and a high of 116.91%. The associated major page fault average was 123.36% with a low of 62.50% and a high of 150.00%. Although the observed container major page fault results show a considerable average increase of 121.74% this equates to just an additional 28 major page faults across a five-minute test run.

Memory utilisation tests recorded the amount of memory used by the system in sole execution of the OS to provide a baseline average. The average OS memory use across all four ECUs was observed at 422902kb. The native test mode results highlight the amount of available memory used to support the ECU functional script's execution. The average increase in memory use during the native test mode was 2495kb. The container test mode includes additional memory required for the ECU functional script as per the native execution but any additional memory needed to support the container ecosystem. Memory utilisation observed across native and container test modes was relatively static once the software had been loaded into main memory. There were minimal additional demands placed upon memory during script execution in either test mode. The average increase in memory use to support container operation was observed at +615.45%, an additional 12333kb of available system memory.

The USS reveals the amount of process allocated memory. The USS test results showed that the functional software script requires considerably more memory when executing within a container environment. To

support the container ECU functional script required an average of 70.93% more available system memory than native operation across all four ECUs. However, when factoring additional memory needed for container-specific processes, this average memory use is observed at 13.07%. Therefore virtualisation, regardless of the method or type, requires more available memory to accommodate each virtual instance, but this is not excessive.

Memory utilisation is a crucial factor in supporting virtualisation. Each virtual instance requires a dedicated portion of available memory and an increase in memory utilisation is expected when implementing a virtualisation solution. However, OS virtualisation through containers is a much lower memory use rate than full system virtualisation techniques ranging within the megabyte rather than gigabyte memory requirements.

6.11 Evaluation of Container Specific Resource Consumption

In order for ECU functional software to function correctly in native mode, it requires various binaries and shared libraries. To port ECU functional software into a container-based environment, several subprocesses initiate and run in the background. Each container is an isolated and immutable client supported by the container daemon, which acts as the server. Each container is constructed from an image consisting of several layers representing process configuration and required software to support the container encased function. This section evaluates the feasibility of running ECU functionalities within containers.

Like all virtualisation solutions, containers require some level of additional system resources. A series of specific resource usage tests were undertaken to examine any additional resources necessary to support the container-based functional software execution. The following CPU and memory use by process tests (Charts 67 – 74) was performed and the resultant metrics recorded.

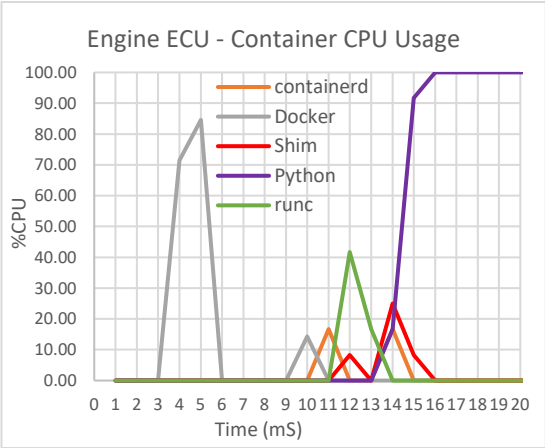


Chart 67: Engine ECU container CPU use by process

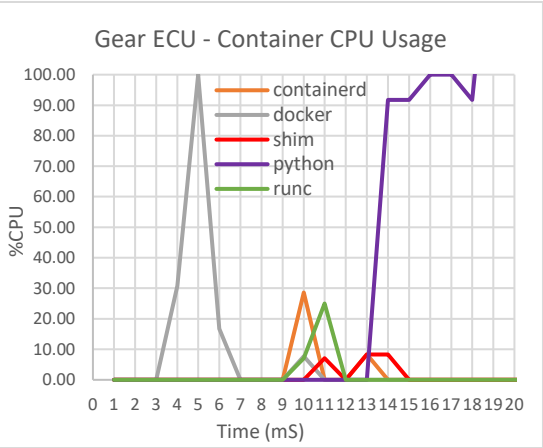


Chart 68: Gear ECU container CPU use by process

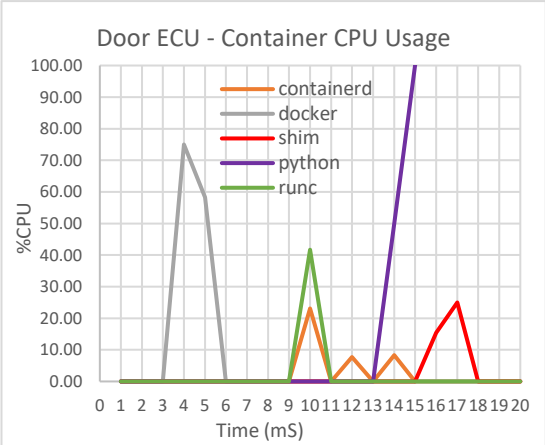


Chart 69: Door ECU container CPU use by process

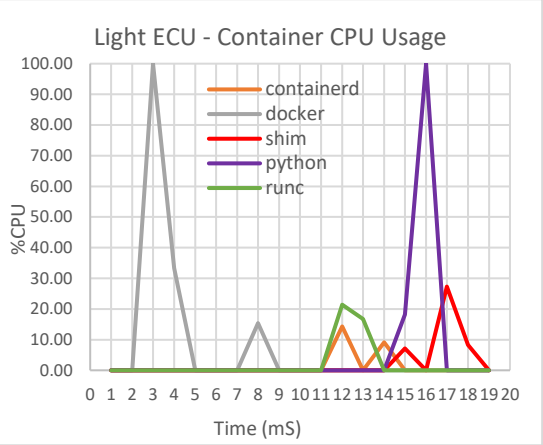


Chart 70: Light ECU container CPU use by process

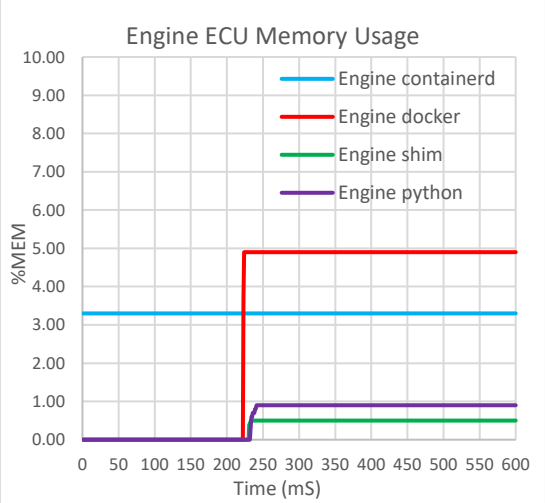


Chart 71: Engine ECU container memory use by process

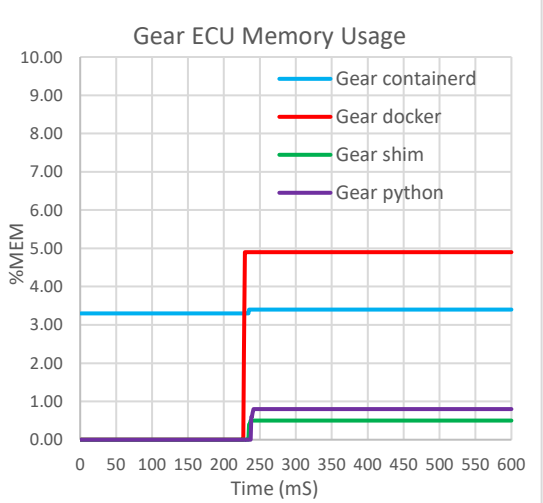


Chart 72: Gear ECU container memory use by process

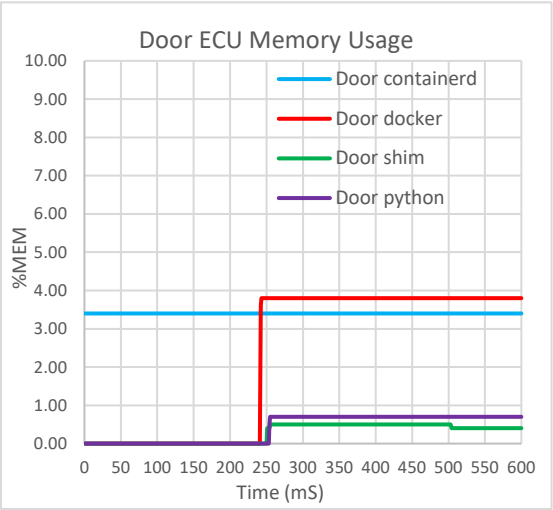


Chart 73:Door ECU container memory use by process

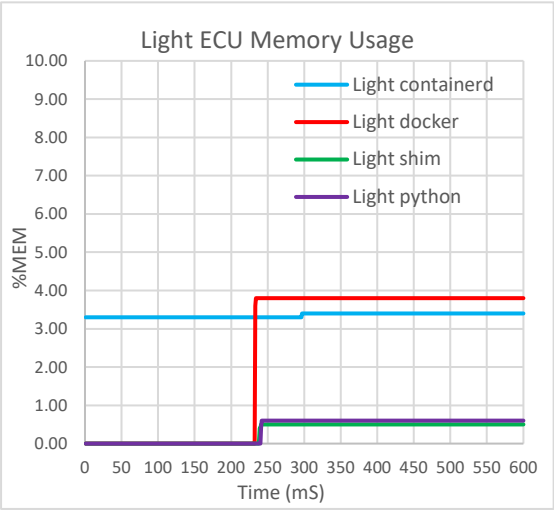


Chart 74: Light ECU container memory use by process

6.11.1 Container CPU and memory use summary

The tool used to measure the container-specific processes was *top*. This generic software tool calculates the specific CPU resources required to initialise and maintain the container environment. Due to the way *top* collects data, the %CPU metric is not %utilisation as observed in previous tests. To obtain a true reflection of how much CPU resource is being used, the %CPU metric must be divided by the number of CPU cores, in this case, four. Therefore, the %CPU represents a maximum of 25% CPU use across all CPU cores or 100% of a single core. As can be observed in Charts 67 – 70, upon execution of the container software, the docker process is the first process to consume CPU resources which initiates the process of starting the container. The *runc* process is a lightweight container runtime process, which incorporates code that interacts with dedicated OS features related to container virtualisation execution. The *runc* process initialises the container and once initialisation is complete, the container is then handed over to the *shim*. The container *shim* is a process that manages the corresponding container. Once the *runc* and container *shim* have completed handover, the python script is automatically executed. The *shim* and *runc* processes consume negligible CPU resources, as reflected in the previous CPU utilisation section. The overall additional CPU utilisation to support the container environment was minimal.

The observed container process-specific memory use is relatively static once the container is initialised and under container *shim* management. The *containerd* process is a constant process initiated during system start-up and is a continuous level from system initialisation to system shutdown. The *containerd* process manages the container lifecycle and is often referred to as an executor of containers. The *container daemon* and *shim* process are initiated to manage and maintain the container shell's memory requirements from the start of container initialisation. The *container daemon* listens for API requests and manages other container configuration functions, including images, networking and volumes, so the overall memory use is notably higher. Once the *shim* has completed its initialisation, the python script executes and allocated memory accordingly.

6.12 Testing the Suitability of Containers and the Possibility of ECU Consolidation

This research focuses on the additional resources consumed by a container ecosystem to support an automotive ECU function distributed across multiple ECUs. Various data sources collected from multiple sensors are sent to the corresponding ECU for processing which are used as part of that ECU functionality or passed to other ECUs to aid in other automotive functionality. The initial tests and resulting data have shown that container-based ECUs provide numerous benefits to the automotive E/E architecture with very little additional resource overhead. The primary resource components tested were CPU and memory saturation and utilisation. One of the principal benefits of a container-based ECU is hosting multiple containers on the same hardware system, thus promoting consolidation of several single-function ECUs.

Some ECU functional software is highly dependent on large amounts of available CPU resources due to high computational factors. Other programs may be more memory intensive and require increased use of available system memory. Other ECU systems produce large amounts of I/O operations otherwise known as I/O bound processes as part of their functionality.

Consolidation is a primary benefit addressed by container-based ECUs. However, to maintain a container's optimal performance when in execution, specific resource-intensive software functions are distributed among container-based ECUs, ensuring no particular resource is being oversaturated or over utilised.

6.12.1 Sample test program script

A test script was written (see Appendix H), which produced a CPU bound process when in execution. The script involves high computation and thus requires a great deal of CPU time to complete execution. The script was written in Python. Its primary function was to compute every square root value between 1 and 1,000,000 (the script code can be found in Appendix H). A single execution of the script repeats this function 1,000,000 times. The script used the Python *timeit* function to measure the time taken to execute this particular piece of code. A complete script execution cycle repeats the function 100 times.

6.12.2 System stress tests

A single execution of the test script completed in an average time of 78.68ms and consumed about 100% of available CPU single-core resource (~25% across all 4 CPU cores) and ~0.1% of the available memory. A series of system-related stress tests were conducted to understand the effects of any additional load applied to the system. The primary metrics recorded for these tests were to investigate any additional CPU resource saturation and utilisation, and script execution time. There were three artificial loads placed on the system, including CPU, memory and I/O. These synthetic loads were applied using the Linux *stress-ng* software tool, which can apply various configurable levels of stress to a computer system. The main focus was any extension to script execution times and additional CPU load and utilisation placed upon the system.

6.12.3 Process priority

As part of regular operation, when a new process starts the process priority, also known as the NICE value, it is automatically set to default by the operating system. Linux NICE levels range from between -20 to 19 where -20 is reserved for the highest priority, 0 is considered the system default and 19 the lowest priority. During native execution where the script is initiated within the OS, the new process's CPU allocation is dependent upon all other system processes running equally. However, this was not the case when starting the same script within a container. By default, the container environment reserves a portion of CPU resource which is allocated to each new container. The same situation can only be accomplished natively

by altering the NICE value of the process at execution. To reflect this native limitation, there were three separate test operation modes, these were:

- Native - the process starts on the OS/hardware with default OS priority.
- High Priority - the process starts on the OS/hardware with the highest priority level.
- Container - the process starts within a container with default priority.

6.12.4 CPU saturation stress load tests

The following stress tests were performed and the resulting average CPU saturation metrics recorded. The following CPU saturation average stress load tests are a 30-second snapshot across each test script execution mode.

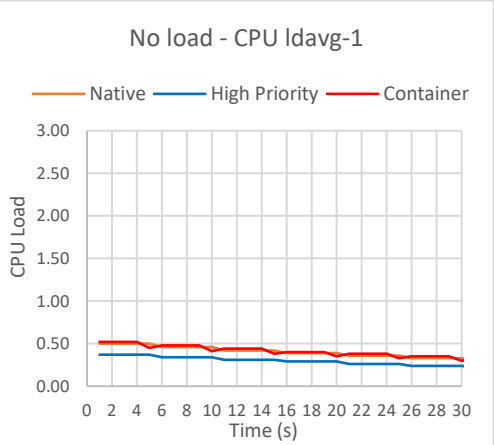


Chart 75: *ldavg*-1 stress test – no applied load

ldavg-1 no-load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.17	0.37	0.23	-
Native	0.24	0.50	0.28	+19.61
Container	0.18	0.52	0.31	+10.17

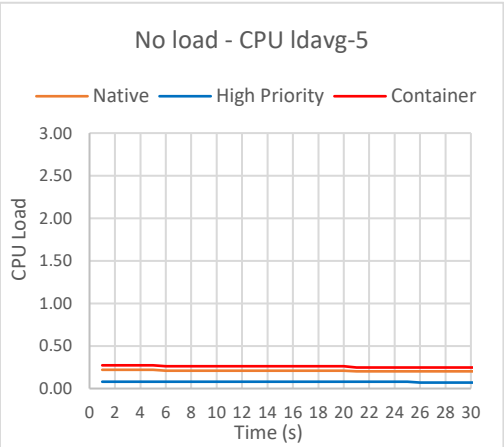


Chart 76: *ldavg*-5 stress test - no applied load

ldavg-5 no-load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.07	0.08	0.06	-
Native	0.19	0.22	0.17	+95.65
Container	0.23	0.27	0.21	+21.05

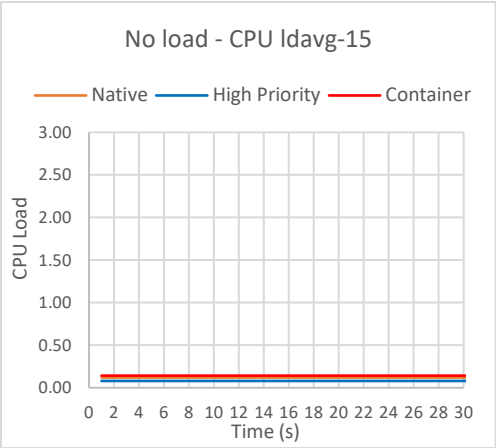


Chart 77: *ldavg*-15 stress test - no applied load

ldavg-15 no-load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.08	0.08	0.08	-
Native	0.11	0.12	0.12	+40.0
Container	0.13	0.14	0.14	+15.38

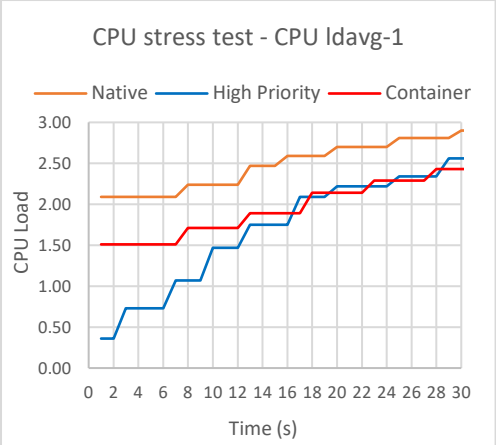


Chart 78: *ldavg*-1 stress test – CPU load applied

ldavg-1 CPU load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.36	2.72	1.84	-
Container	1.51	2.55	2.04	+10.31
Native	2.09	2.99	2.56	+22.61

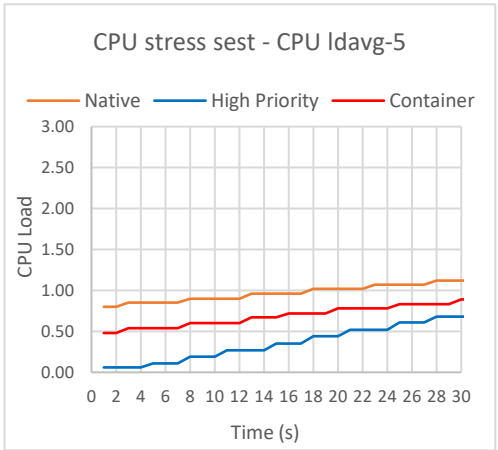


Chart 79: *ldavg*-5 stress test – CPU load applied

ldavg-5 CPU load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.06	0.83	0.43	-
Container	0.48	0.94	0.73	+51.72
Native	0.80	1.17	1.00	+31.21

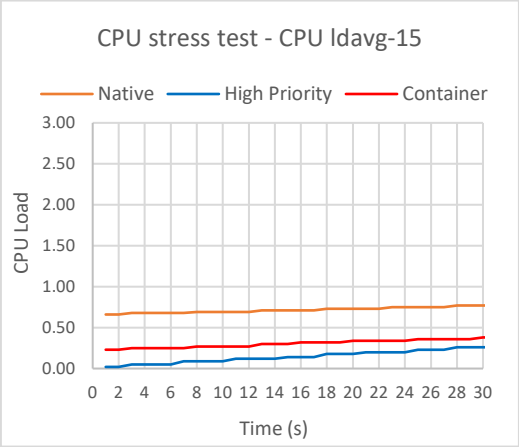


Chart 80: *ldavg*-15 stress test - CPU load applied

ldavg-15 CPU load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.02	0.31	0.17	-
Container	0.23	0.40	0.32	+61.22
Native	0.66	0.79	0.73	+78.09

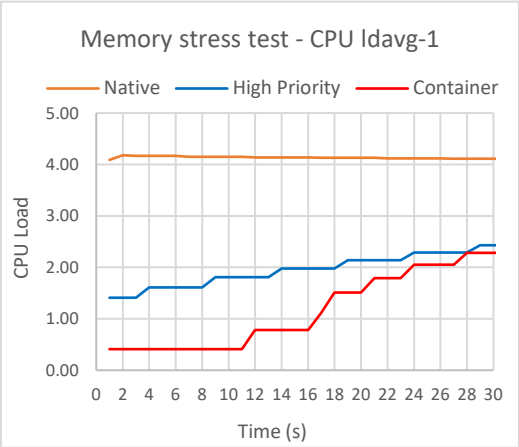


Chart 81: *ldavg*-1 stress test - memory load applied

ldavg-1 memory load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.57	2.88	2.06	-
Container	0.41	3.06	1.78	-14.58
Native	2.70	4.18	4.02	+77.24

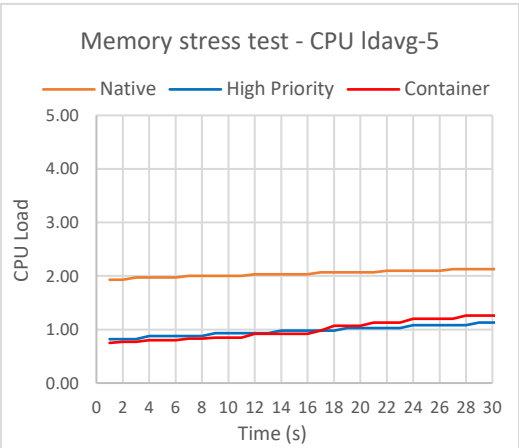


Chart 82: *ldavg*-5 stress test - memory load applied

ldavg-5 memory load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.65	1.32	1.03	-
Container	0.75	1.50	1.16	+11.87
Native	1.51	2.19	1.99	+52.70

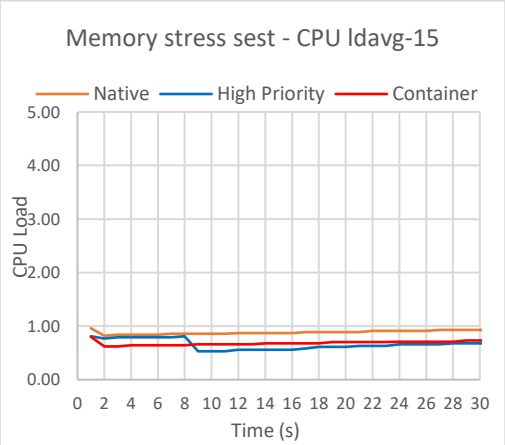


Chart 83: *ldavg*-15 stress test - memory load applied

ldavg-15 memory load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.53	0.81	0.69	-
Container	0.56	0.80	0.71	+2.86
Native	0.67	0.96	0.86	+19.11

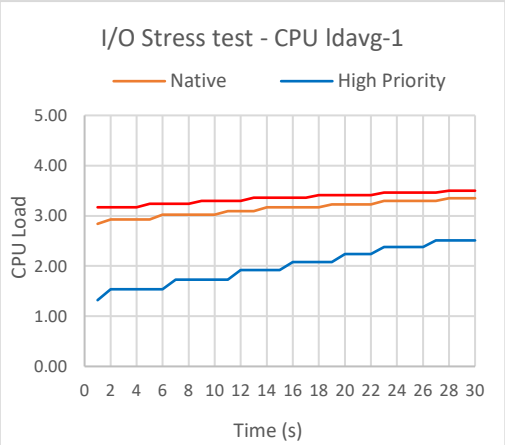


Chart 84: *ldavg*-1 stress test - I/O load applied

ldavg-1 I/O load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.38	2.84	2.06	-
Container	2.46	3.61	3.30	+46.27
Native	2.35	3.45	3.11	-5.93

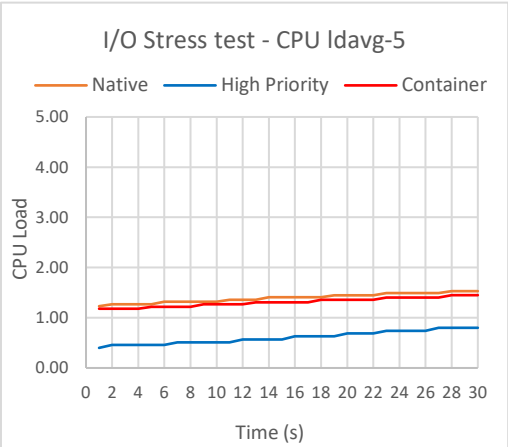


Chart 85: *ldavg*-5 stress test - I/O load applied

ldavg-5 I/O load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.19	0.95	0.65	-
Container	0.94	1.57	1.30	+66.67
Native	1.08	1.62	1.40	+7.41

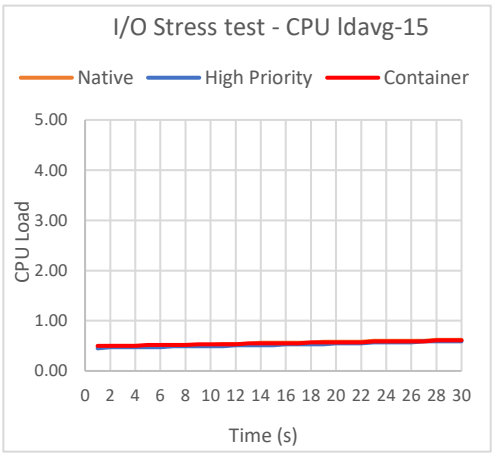


Chart 87: *ldavg*-15 stress test I/O load applied

ldavg-15 I/O load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	0.39	0.64	0.54	-
Container	0.41	0.66	0.55	+1.83
Native	0.43	0.65	0.56	+1.80

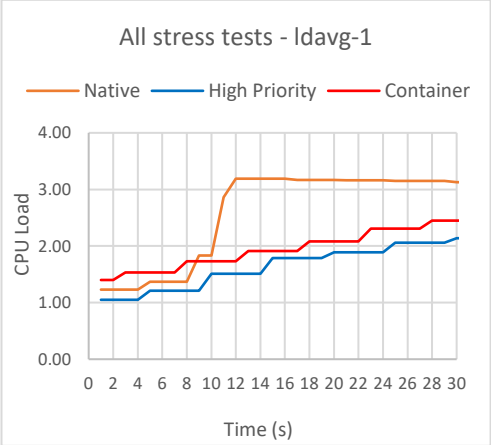


Chart 88: *ldavg*-1 stress test - all loads applied

ldavg-1 all load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	1.05	2.84	2.34	-
Container	1.23	2.98	2.68	+13.55
Native	1.40	3.19	2.93	+8.91

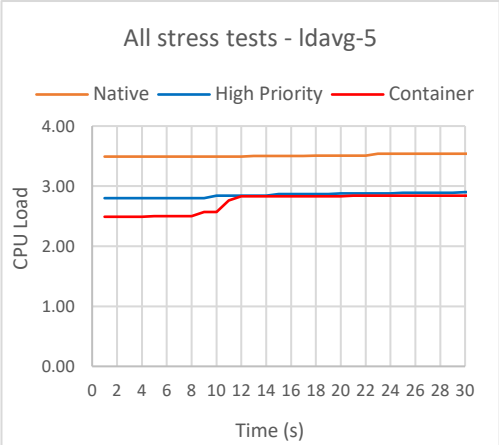


Chart 86: *ldavg*-5 stress test - all loads applied

ldavg-5 all load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	2.49	2.87	2.74	-
Container	2.80	2.94	2.83	+3.23
Native	3.46	3.61	3.44	+19.46

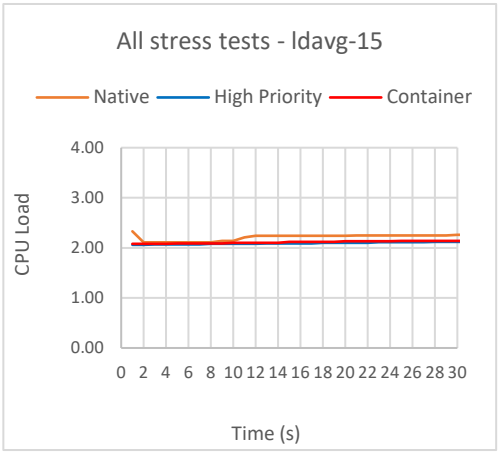


Chart 89: *ldavg*-15 - all loads applied

ldavg-15 all load stress applied				
	Low Load	High Load	Average Load	%diff
High Priority Native	2.06	2.23	2.17	-
Container	2.08	2.23	2.17	0.00
Native	2.11	2.33	2.23	+2.73

6.12.5 CPU saturation stress load test analysis

As expected, when the system was under no external stress load, the native high priority execution exhibited the smallest saturation levels and the container average had the highest CPU saturation levels. However, across all triplet load tests, the highest recorded saturation level was 0.52 (52% across a single CPU core), observed during one of the container triplet tests.

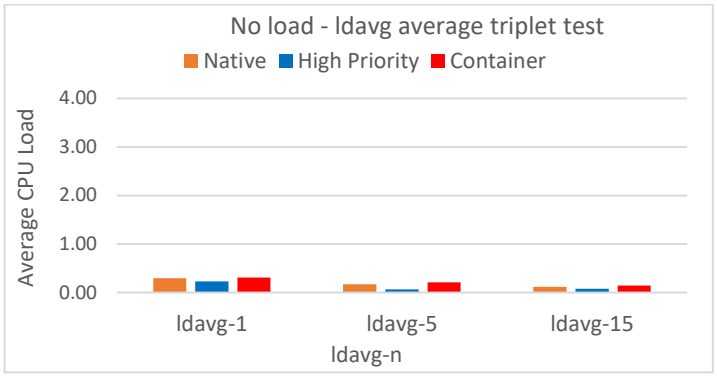


Chart 90: *ldavg* triplet test - no applied load

As shown in Chart 91 below, the container CPU load averages outperformed the native execution when under CPU stress load:

- *ldavg*-1 +22.61% when compared with container execution
- *ldavg*-5 +31.21% when compared with container execution
- *ldavg*-15 +78.09% when compared with container execution

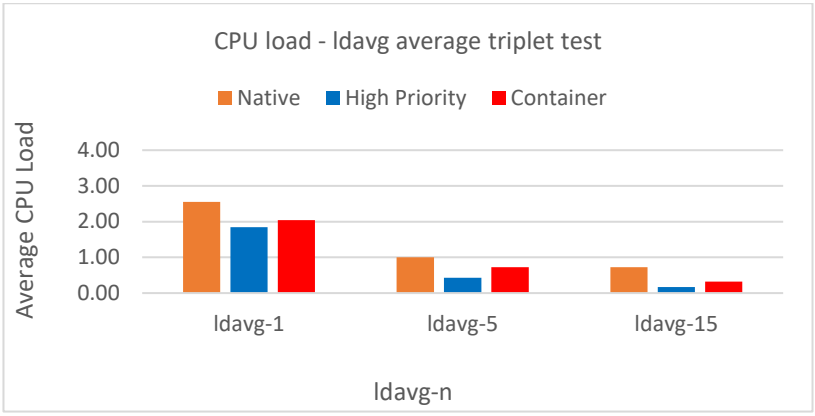


Chart 91: *ldavg* triplet test - CPU load applied

During the memory stress load tests, the native *ldavg*-1 and *ldavg*-5 triplets experienced the highest CPU saturation levels across all four sample. The container *ldavg*-1 results were lower than the native triplet tests, which ranged from +77.24% to +19.11%. When placed in memory load stress, the CPU saturation under container execution was similar to the high priority native performance. The *ldavg*-1, 5 and 15 load averages for the container were recorded at -14.58%, +11.87% and 2.86%, respectively.

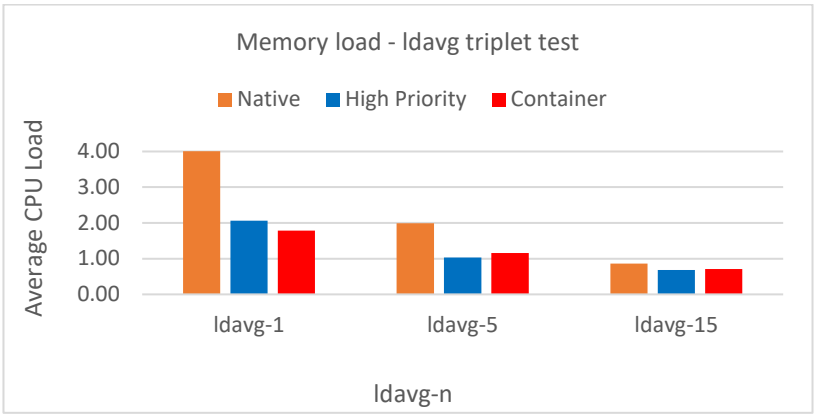


Chart 92: *ldavg* triplet test - memory load applied

The I/O stress load test showed that the load placed on the container was greater than either of the native or high priority execution modes during the *ldavg*-1 triplet test. Native high priority execution outperformed both native and container execution.

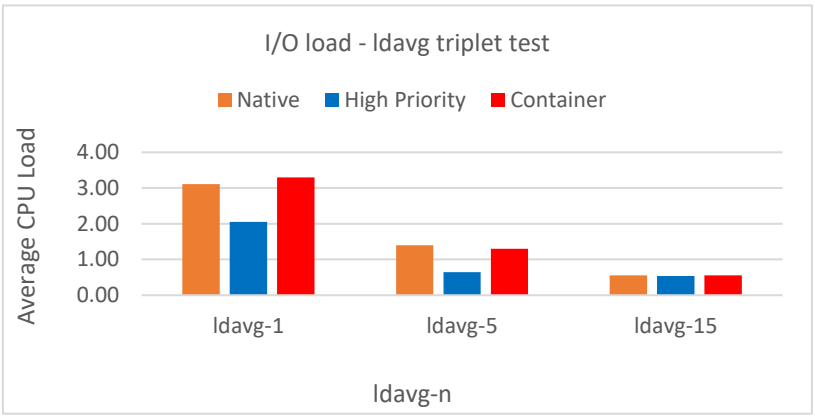


Chart 93: *ldavg* triplet test - I/O load applied

With I/O stress load, applied container execution was comparable with native execution where native increases were observed below 10%.

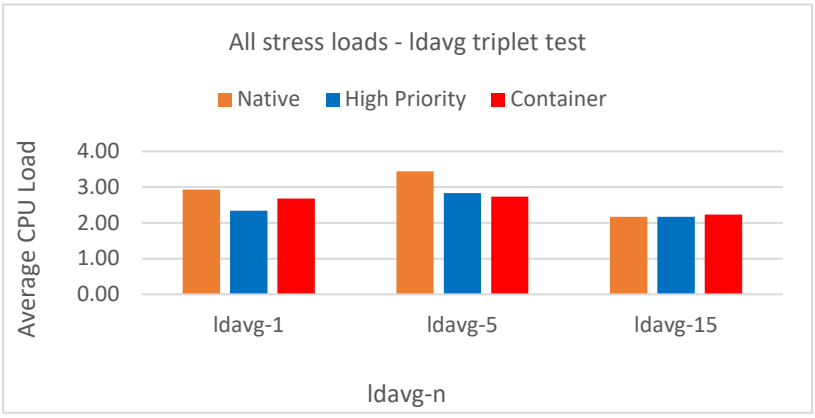


Chart 94: *ldavg* triple test - all loads applied

When applying all three stress loads, all three execution states exhibited the highest average CPU saturation levels. This was anticipated because of the excessive load stresses placed on the system. This particular test result reveals that regardless of the execution test mode, CPU saturation is relatively constant throughout the *ldavg* triple tests. Specifically, across the *ldavg*-15 triplet, the increase from each test execution was between 0.00% and 2.73%.

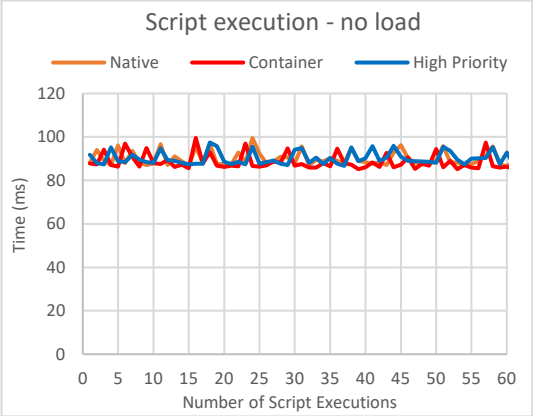


Chart 95: Script execution times - no applied load

Script Execution with no load stress					
	MIN	MAX	Avg.	%diff.	
High Priority Native	86.68	97.46	89.68	-	-
Container	84.73	99.54	87.65	-2.26	-
Native	86.36	99.49	89.64	2.27	-0.044

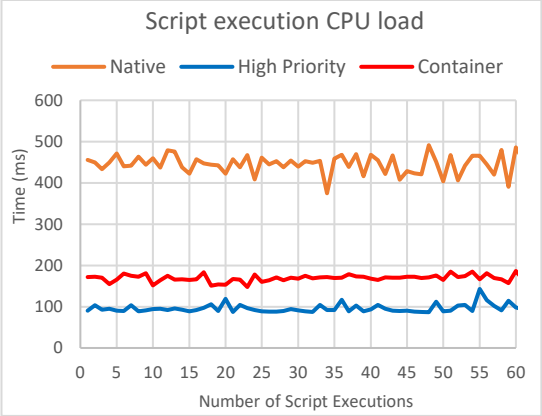


Chart 96: Script execution times under CPU load

Script Execution with CPU load stress					
	MIN	MAX	Avg.	%diff.	
High Priority Native	86.66	142.97	95.76	-	-
Container	147.67	186.48	169.72	77.23	-
Native	374.73	509.18	444.89	162.13	364.58

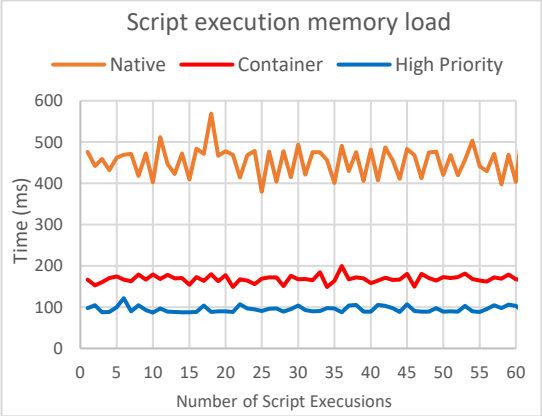
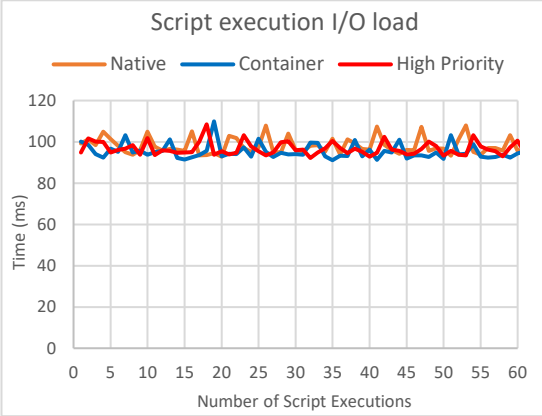


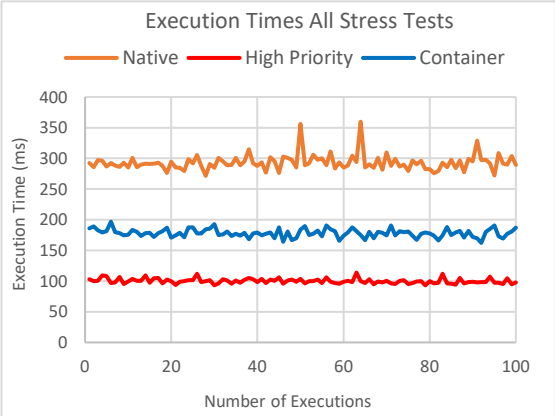
Chart 97: Script execution times under memory load

Script Execution with memory load stress					
	MIN	MAX	Avg.	%diff.	
High Priority Native	86.10	121.91	94.02	-	-
Container	148.82	199.60	168.56	79.28	-
Native	379.49	568.75	452.67	168.55	381.46



Script Execution with I/O load stress					
	MIN	MAX	Avg.	%diff.	
High Priority Native	92.17	108.47	96.26	-	-
Container	91.10	109.92	94.65	-1.67	-
Native	89.68	107.95	97.17	2.66	0.94

Chart 98: Script execution times under I/O load



Script Execution with all load stress					
	MIN	MAX	Avg.	%diff.	
High Priority Native	92.98	113.83	100.02	-	-
Container	162.17	196.81	178.22	78.18	-
Native	271.45	359.71	293.11	64.46	193.05

Chart 99: Script execution times under all loads

6.12.6 Script execution time analysis

Under zero load, the high priority native tests exhibited the quickest average script execution across all applied stress loads as observed in Chart 95. During the high priority native script execution, the average execution times were 89.68ms to 100.02ms regardless of the system's stress load. I/O stress load had no bearing on script execution time. For example, comparing average execution times, there was an average increase of 10ms across all three test script execution modes. In contrast, placing the system under CPU and memory stress loads had a considerable detrimental effect on native script execution times where the average script execution increased to 448ms. When comparing the container execution test mode with the high priority native test mode, the execution time increased across CPU and memory stress loads were observed at approximately 78ms, see Chart 96 and 97. With the NICE value set to the highest userspace

priority level script, execution times were constant regardless of applied stress load. The average execution time for the native high priority script execution was 89.14ms which is a variance of between 0.61% and 12.21%. The container script execution test across CPU, memory and all applied stress loads exhibited a consistent average execution time between 168 and 178ms.

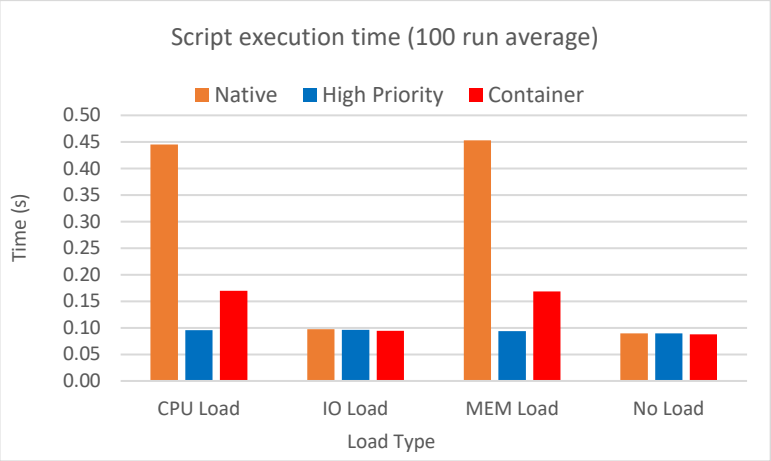


Chart 100: Script execution time run average

As seen in the chart above, under excessive CPU loads, the container outperformed the native average execution times by 162.13%. Similarly, under extreme memory loads, the container outperformed the native average execution times by 168.55%.

6.12.7 CPU utilisation (%user + %system) with applied Load

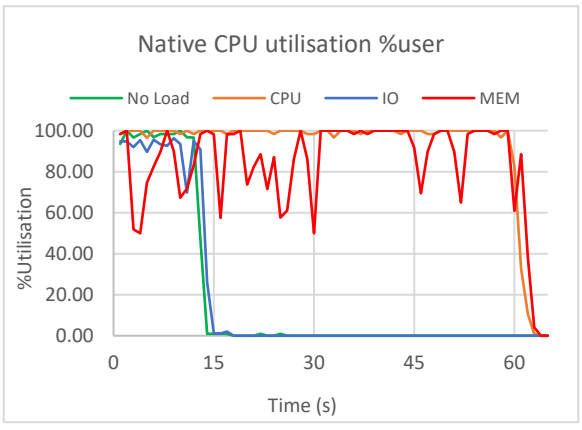


Chart 101: Native CPU %user utilisation

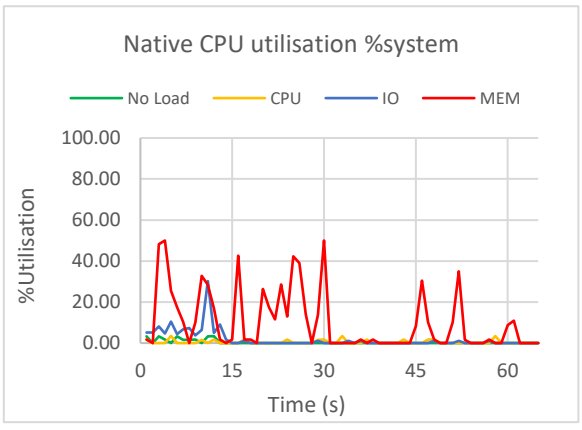


Chart 102: Native CPU %system utilisation

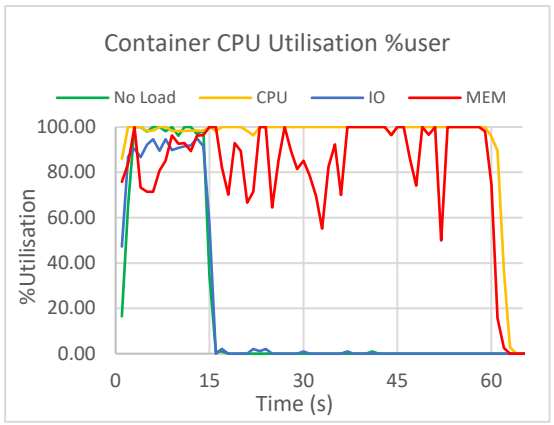


Chart 103: Container CPU %user utilisation

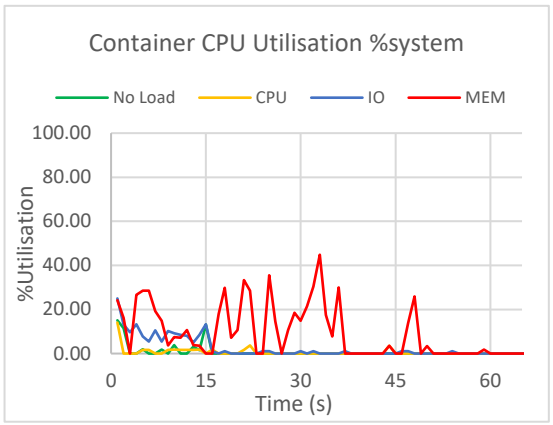


Chart 104: Container CPU %system utilisation

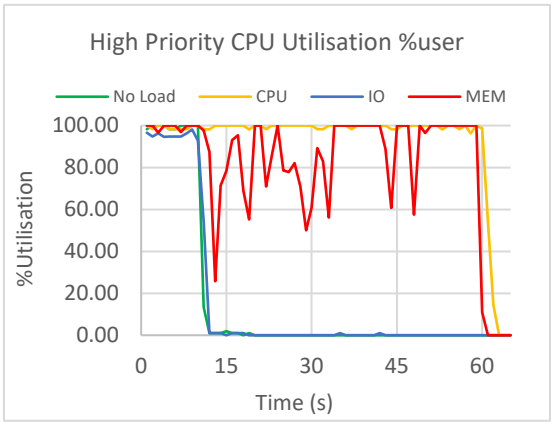


Chart 105: High priority %user CPU utilisation

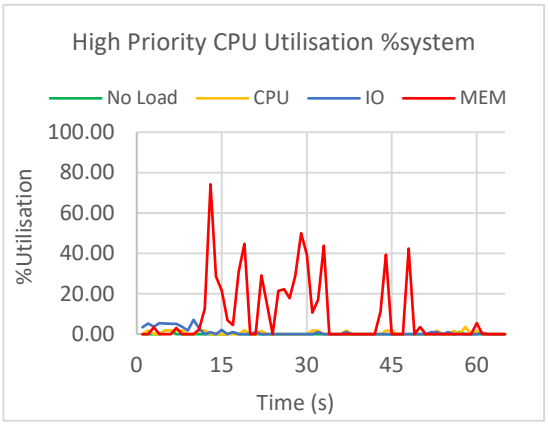


Chart 106: High priority %system CPU utilisation

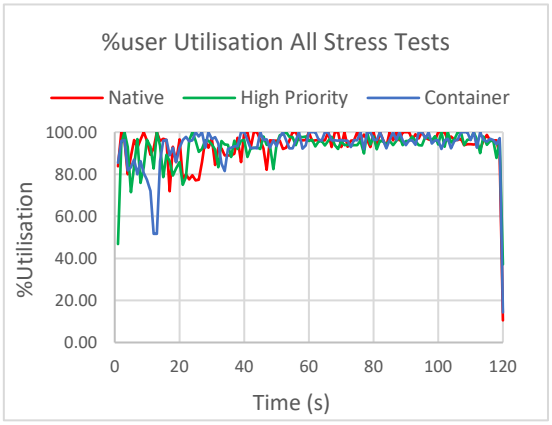


Chart 107: %user - all stress tests applied

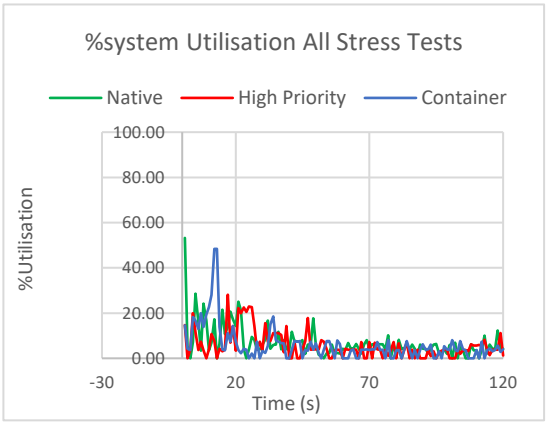


Chart 108: %system - all stress tests applied

6.12.8 CPU utilisation with applied load analysis

As observed in the preceding graphs, under all three test modes, script execution was completed at around 15 seconds after implementation when no stress load or I/O stress load had been applied. In both CPU and memory stress load tests across all three test modes, execution times increased to approximately 60 seconds.

The highest CPU utilisation activity levels were exhibited during the memory stress load tests across all three test operation modes. A drop in %user CPU utilisation was mirrored by an increase in %system CPU utilisation. Across all tests, there was very little CPU utilisation across any of the execution test modes when I/O stress load was applied. As expected, high CPU utilisation was observed when CPU stress load was applied due to the additional CPU tasks created by the stress tool.

6.12.9 Container suitability summary

During the CPU saturation tests, native test mode experienced some of the highest saturation levels shown in Charts 75 - 89, especially when applying memory stress loading, as observed in Charts 81 - 83. Throughout the I/O stress loading tests, the container test mode during the *ldavg*-1 test experienced the highest CPU saturation levels, equivalent to native operation across the *ldavg*-5 and *ldavg*-15 metrics. As expected, altering the NICE value to a higher priority enabled a more responsive system in almost all cases.

Observed script execution times were highest when applying CPU and memory load stress, particularly during native execution. The average time taken to complete a single script execution was 568ms under memory stress load and 509ms under CPU stress load. The high priority script execution exhibited the lowest execution times across all individual stress load tests, as expected, with a combined total script execution average of 100ms. The container execution performed well under all stress load conditions, especially under CPU and memory loads where the average execution time was 170ms, which was 114% lower than the native script execution times.

The designed test script produced a CPU bound process and higher levels of CPU utilisation were observed across all three test modes. Under the native test with no stress load, script execution was completed at

around 15 seconds with almost 100% %user CPU utilisation and very little %system activity. During the CPU load stress tests, similarly high levels of CPU utilisation were exhibited. Complete script execution time extended to approximately 60 seconds. This fourfold increase in execution time was primarily due to the script process competing with other stress loads placed on it. The memory test showed similarly high levels of %user CPU utilisation and periods of high levels of %system where the memory load test was invoking additional kernel activity.

The CPU experienced higher levels of CPU utilisation when the system was placed under memory stress load. The memory stress load tests invoke several different memory-related system tasks, including memory allocation and I/O operations. Time spent in the kernel should be kept to a minimum, ensuring overall system response and efficiency. Altering the NICE value of a task can lead to CPU overload or an unresponsive system. Manually setting a NICE value greater than zero to an individual process or task increases its priority resulting in more CPU time and resources allocated to that particular task. In a multitasking system where, multiple processes and tasks are competing for CPU time, tasks with a higher priority can cause system bottlenecks for lower priority tasks and processes, whilst they wait for higher priority tasks to complete. When the CPU is spending excessive amounts of time and resource servicing %system processes and tasks, it has less availability overall to dedicate resources to %user processes and tasks where userspace programs are running.

Containers do not suffer from the same slow response time issues experienced when system stress occurs at the native level. Containers utilise a Linux kernel feature known as control groups (*cgroups*). This Linux OS feature specifies how the kernel allocates resources to groups of processes. Linux based containers rely on *cgroups* to share hardware resources as well as limiting an application to a set of resources or dedicating additional resources to a particular container when required. When creating a container, *cgroups* set the necessary level of hardware resources. Focusing on CPU load average, script execution times and CPU utilisation, the container test performance was closely matched to the native high priority test in almost all respects without manually elevating the process priority. In terms of consolidation, container performance is slightly affected by excessive I/O operations. Nevertheless, combinations of CPU and memory-bound

processes do not overly affect system saturation, utilisation or program execution times, which are comparable in speed to high priority processes.

Chapter 7 Software Update Evaluation

Objectives

- Provide an overview of current automotive software update procedures.
- Investigate the benefits of container-based automotive software updates.
- An overview of container images concerning automotive software updates.
- Define the types of container-based automotive software updates.
- Test checkpoint and restore procedures on a container.

7.1 Introduction

Whilst more vehicle subsystems have become digitised, there is an ever-increasing risk of software bugs, errors and vulnerabilities, which must be rectified promptly once discovered. Chapter 3 has identified that one of the principal mechanisms in resolving an automotive software failure is the “return or recall”. However, this has its own limitations including cost to the manufacturer and inconvenience to the consumer. In order to address these limitations, a new approach to automotive software updates is required. One possibility exists within smart devices and computing technology, which are updated periodically to provide software bug fixes and the latest security patches, and add new software functionality or install newer versions. This is enabled through the device’s own connectivity hardware. The benefits of this connectivity technology have been recognised by the automotive industry and in recent years has become increasingly more popular within new vehicle models. Furthermore, connectivity technology can play a crucial role in enabling automotive OtA software updates, which can address the identified issues concerning the return/recall method currently employed throughout the industry.

According to a comparative study conducted by Halder et al. (2020), most car manufacturers only support OtA software updates for GPS maps, navigation and infotainment systems (see also Placho et al., 2020). However, Tesla has embraced OtA software updates and has extended its use to many aspects of the vehicle’s ADAS and power management systems. Nevertheless, there are no vehicle manufacturers currently addressing OtA software updates outside of these limited systems, i.e. GPS maps, infotainment, ADAS and power management.

An automotive E/E architecture which incorporates container-based ECUs can offer many benefits concerning standard ECU software updating, including application and OS software. The confines of optimised ECU hardware architectures do not apply to container-based ECUs. The research presented in this chapter investigates how software updates can be applied to a container-based ECU.

7.2 Current Automotive Software Re-flashing Techniques

The current practice of updating automotive ECUs involves software flashing or re-flashing techniques (Onuma et al., 2018). The operating system and functional software of an ECU are generally held within embedded FLASH memory. Depending upon the model, modern motor vehicles can have hundreds of megabytes of FLASH memory spread across their ECUs. Under the return or recall mechanism, flashing or re-flashing software is often completed by authorised personnel requiring the vehicle to be offline. According to a whitepaper by NXP (2013), new or updated software content must conform to several requirements when being applied to a target ECU:

- Safety – new software cannot be the cause of system failure. There needs to be some mechanism whereby software can be rolled back to a last known good state.
- Security – the integrity of any new software must be verified, ensuring a third party has not intercepted and altered the source code. Non-approved entities must not be able to perform a software update on the target system.
- Transparency – regardless of how new software updates are conducted, they must not impact the driver's intended use of the vehicle.

New software is delivered to the target ECU in one of two formats - full binary and diff/Delta file (Mckenna, 2016).

7.2.1 Full binary re-flashing

ECU firmware is updated in its entirety through a process known as re-flashing, which conforms to ISO 14229-3/UDS and ISO 15765-2/DoCAN. As part of this process, the entire ECU software image is replaced with a newer version and the time taken to update the software can often take hours to complete. This in part depends on the size of the software update, the destination memory, protocol and whether encryption is used (Howden, et al., 2020). Data compression algorithms offer one approach in reducing high re-flash times with varying advantages and disadvantages (Suzuki, et al., 2019). The previously installed software has no relevance on the new update, which can be beneficial if the previous version requires replacing in

its entirety rather than upgrading specific parts. The size of the image binary impacts the time taken to transmit and download the file. The new updated software image must also be stored within the target ECU, which requires redundant storage, potentially of an undetermined fixed amount in order to accommodate any future software update (Mugarza et al., 2018).

7.2.2 Difference/delta file

Diff/delta file flashing is a concept that compares the base file with the new version file and creates a delta or difference file, thus reducing the size of the update (Stegar et al., 2017). Compared with a full binary software update, a diff/delta software update is approximately <10% of the full binary file size. Diff/delta files are much quicker to transmit, decreasing overall transmission time by up to 90% (Bogdan et al., 2016). This method requires considerably less redundant storage but it is reliant on the previous ECU software version. A patching algorithm block erases the old data and writes new data in its place.

7.3 Benefits of Container-Based Automotive Software Updates

Containers offer many benefits to current and future automotive E/E architectures. For example, they provide a standardised environment that can facilitate automotive embedded software updates and their hardware is not fixed to a particular version or type of software. Consolidation is a crucial benefit of container ECUs where multiple containers operate on larger, more resource capable embedded hardware platforms. Containers are constructed from images based on a layered architecture. A container image incorporates one or more layers which define all required software, libraries and binaries, and configuration settings for any subsequent containers created from that image. Therefore, a container-based ECU must also conform to the three principles of safety, security and transparency, as mentioned previously:

- Safety – new software containers can be rolled back to the ‘last known good’ image and known safe containers can be reinstated.
- Security – new container images can be either pulled from an authorised repository to the target vehicle or pushed by the manufacturer. All image layers utilise, for example, SHA256 encryption and the checksum's validation before the image goes ‘live’.

- Transparency – new container images, once validated, can be checked within a sandbox area of the vehicle's automotive E/E architecture before deploying live containers, ensuring the updated system's safe and continued service.

7.4 Types of Container-Based Software Updates

Current software upgrades and bug fixes require the car to be shut down whilst being updated and subsequently brought back online when complete. Looking towards the automotive industry's future, OtA is a software update mechanism that relays software from source to destination, utilising vehicle connectivity. OtA updates can address customer disruption and the intrinsic delay between the availability of a new software update and the deployment of that update to the target vehicle. Through vehicle connectivity, new automotive software updates can be pushed or pulled to the target vehicle at any time. However, the current primary focus of OtA is on applying a new update when the vehicle is solely offline. The modern motor car is a system which operates utilising many subsystems of mixed-criticality. When in operation, there are numerous safety-critical and continual service systems that require a real-time response. The criticality of the software-related issue often determines the required type of software update response. This research has identified three distinct container-based automotive software update modes: offline, online and dynamic.

7.4.1 Offline update

Offline updates are initialised when the vehicle is powered down. Once the software update verification and initial container creation are complete, any updates applied are available when the vehicle is next started, similar to a system proposed by Tobolski et al. (2018). This process mirrors the current return or recall procedure but does not incur any associated disruption to the manufacturer or consumer, or recall costs (Furst and Bechter, 2016; Onuma et al., 2018; Herberth et al., 2019). Furthermore, this type of update mechanism can be utilised for multiple system updates, which may affect numerous subsystems across different automotive domains or involve safety-critical systems that cannot be updated safely with the vehicle in operation.

7.4.2 Online update

New software updates can be pushed or pulled to the vehicle using onboard connectivity and applied whilst the vehicle is powered up but not in operation. The update process is initiated and a new container is created from the new updated image. The affected subsystem is then temporarily shut down before the new container's initialisation with the updated software. This update method could be applied to any automotive system but only where a system's required initialisation does not incur long time delays. For example, small and frequent periodic updates and software security patches would be ideal candidate systems and functions.

7.4.3 Dynamic update

DSU do not require the system to be taken offline (Seifzadeh et al., 2013). As such, they provide an essential service where systems must offer a 100% uptime (Neamtiu et al., 2006; Hayden et al., 2012). Taking a system offline to fix bugs, improve system performance or extend functionality causes delay and disruption. Driverless vehicular technology promises non-stop long-haul trucks and round-the-clock lift-hailing rides and therefore the window to administer software updates become shorter and downtime is a significant disruption (Hörl, 2017; Shankwitz, 2017; Simpson et al., 2019). For the purposes of this research, a DSU refers to a vehicle sub-system that can be updated and made available once completed, without the vehicle requiring shut down and whilst it is still in a mode of operation. This type of automotive update is suited ideally to any automotive function which is not involved in vehicle operation or safety. Potential systems could include security software updates and patches, any software relating to autonomous driving functions which are not in operation and passenger-related systems relating to comfort, heating and occupant-vehicle interaction.

7.5 The Case for Dynamic Software Updates

DSU should be reserved for those critical instances where urgency in rectifying a software-related issue must be conducted as soon as possible to maintain the integrity of the vehicle and safety of the occupants (Gasper and Markelj, 2018). A scenario that could benefit from a DSU may involve an automotive software

vulnerability, which if compromised, could enable access to vehicle safety-critical subsystems including engine, braking and steering, as seen in 2015 by Miller and Valasaek (2015). This type of attack is of particular concern in vehicles capable of autonomous driving functions and with connectivity features. It can be executed remotely and potentially affect an entire fleet of vehicles (ENISA, 2019).

To be updated dynamically, automotive subsystem updates should not interfere with the primary system that would cause it to cease operation or place it in an unsafe or error state. To accomplish the DSU goal, Hicks and Nettles (2005) have defined several criteria:

- Flexibility - any part of the vehicle subsystem should be updateable without requiring downtime.
- Robustness – errors should be minimised.
- Ease of use - the update procedure should be easy to use.
- Minimal overhead - a software update should have little impact on the overall system and subsystem performance.

7.6 Current Automotive DSU Techniques

Although there is an array of literature on DSU techniques (Hayden et al., 2012; Seifzadeh et al., 2013; Mugarza et al., 2018), there is little regarding its use within an automotive E/E architecture context with the notable exception of DySCAS (Richard et al., 2007). The DySCAS project was a collaborative venture between automotive manufacturers and suppliers, which ran between 2006 and 2008, with the aim of provisioning a new automotive architecture. This new architecture promoted a dynamically reconfigurable automotive control system when new hardware and software functionality or closed system re-configuration was introduced (Richard et al., 2007). Whilst not a true DSU system, it added considerable complexity to the automotive E/E architecture (Axelsson and Kobetski, 2013).

A true DSU mechanism is achieved through either a system or a software-based approach:

- A system approach achieves DSU through redundant hardware. The primary system operates until an upgrade is required, at which point the secondary or redundant system is started. The primary

system state, including existing network connections, computational state and open files, is transferred to the redundant system (Mugarza et al., 2018).

- A software-based approach transforms the current process state through a state transformation function into an equivalent state of the new updated process. It complies with logical as well as temporal correctness through:
    - Dynamic linking – shared libraries are loaded into new processes and linked to new software code required at program runtime.
    - Re-linking – new definitions are made by utilising new code. Afterwards, an update must be linked to the old code to maintain operational consistency.
    - State transfer – active function states must be transferred to conform with the new updated code to maintain state correctness and continue program execution.

Of the two approaches, the system approach is counterproductive when considering cost, power use, weight and space constraints. Consequently, this research utilises the software approach through image layer updates and Checkpoint and Restore In Userspace (CRIU).

7.7 The Benefits of Container Images to Automotive Software Updates

Multiple containers can be created from the same image, which consists of several read-only layers. Image layers represent specific data, software, hardware and network configuration parameters. Any change to the image is specific to a particular layer. Only a layer which has been modified is subsequently updated within the image. Small image configuration changes or an update to a specific piece of software within the image will prompt the system to download only the layers which pertain to those particular changes. Figure 35 below represents a typical container image and associated individual stacked layers.

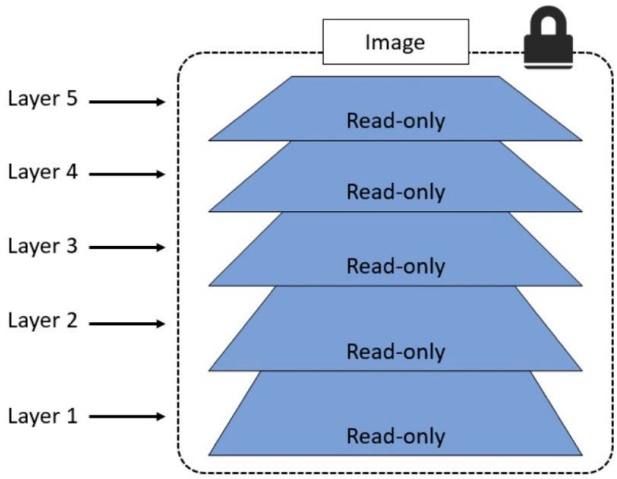


Figure 36: Container Image layers

A further benefit of this layered approach is the ability to share image layers between separate images. Multiple images that share common layers promote efficiency. A layered design boosts image download speed and minimises the overall image footprint and storage requirements.

7.7.1 Independent image download

The example below illustrates two similar images (alpine-python2 and alpine-python3), both of which share a common OS (alpine), but have different versions of application software (python2 and python3). The first example, Figure 37, illustrates the three distinct image layers associated with the alpine-python2 image. Figure 38 also comprises of three layers, two of which are the same as those shown in Figure 37.

```
master01:~/images docker pull digitalgenius/alpine-python2-pg
Using default tag: latest
latest: Pulling from digitalgenius/alpine-python2-pg
cbdbe7a5bc2a: Pull complete
136e07eea1d6: Pull complete
f890c681a889: Pull complete
Digest:
sha256:c4cff01d2c59c13fb729c158bb309194fb469bc28117e70b535bf48d4aac82de
Status: Downloaded newer image for digitalgenius/alpine-python2-pg:latest
docker.io/digitalgenius/alpine-python2-pg:latest
```

Figure 37: Independent Image download – alpine-python2 Image

```
master01:~/images# docker pull digitalgenius/alpine-python3-pg
Using default tag: latest
latest: Pulling from digitalgenius/alpine-python3-pg
cbdbe7a5bc2a: Pull complete
136e07eea1d6: Pull complete
1a5281d561d0: Pull complete
Digest:
sha256:0b1512a41129f127bd512185873e351e89cd647a6b32856c8f4ba4aef1b9921b
Status: Downloaded newer image for digitalgenius/alpine-python3-pg:latest
docker.io/digitalgenius/alpine-python3-pg:latest
```

Figure 38: Independent Image download – alpine-python3 Image

Table 17 below displays the time taken to download and extract each alpine image and the total size on disk that the two images require in MB. This individual image download is a standard procedure in software updating. If both images are downloaded independently, each image is downloaded in its entirety and bears no relationship with the other image, even though they both share the same underlying OS (alpine).

Image Name	Version	Compressed Image size	Total size on disk after extraction	Time taken to download and extract image	Additional download time required
alpine-python	2	115.2MB	883MB	23.4335s	-
alpine-python	3	153.53MB		31.3837s	7.9502s

Table 17: Standard image download and extraction times and storage requirements

The following test uses the same alpine-python images. However, before a new image is downloaded, the container host will examine all locally stored images and check for common layers between existing images. If any duplicate layers are found, only those unique layers relating to the new image are downloaded. This is illustrated in Figures 39 and 40. In this test, an existing image contains two identical layers in common with the new image. Therefore, only one layer of the new image is downloaded, which is observed in Figure 40.

```
master01:~/images/alpine-python2-pg
default tag: latest
latest: Pulled from digitalgenius/alpine-python2-pg
cbdbe7a5bc2a:
136e07eea1d6:
f890c681a889:
Digest:
sha256:c4cff01d2c59c13fb729c158bb309194fb469bc28117e70b535bf48d4aac82de
Status: Current stored image from digitalgenius/alpine-python2-pg:latest
docker.io/digitalgenius/alpine-python2-pg:latest
```

Figure 39: alpine-python2 Image in local repository

```
master01:~/images# docker pull digitalgenius/alpine-python3-pg
Using default tag: latest
latest: Pulling from digitalgenius/alpine-python3-pg
cbdbe7a5bc2a: Already exists
136e07eea1d6: Already exists
1a5281d561d0: Pull complete
Digest:
sha256:0b1512a41129f127bd512185873e351e89cd647a6b32856c8f4ba4aef1b9921b
Status: Downloaded newer image for digitalgenius/alpine-python3-pg:latest
docker.io/digitalgenius/alpine-python3-pg:latest
```

Figure 40: alpine-python3 image download

During the alpine-python3 image download, the two duplicate layers are not downloaded. These two layers represent the alpine OS which both python images share. Only the updated python version layer is pulled from the repository. The benefits of layer sharing between container images include reducing the download time for any software update and minimising overall image footprint. Table 18 below highlights the reduced size on disk of both images, which was observed at 44.96%. A reduction in download times between the alpine-python3 images was 5.6346s across the two tests. Reducing storage requirements for individual software images benefits automotive systems by minimising hardware costs. Furthermore, layer sharing promotes quicker download speeds and reduces the impact on OtA bandwidths.

Image Name	Version	Layer	Layer Size	Size on Disk after download and extraction	Time Taken to Download and Extract Image	Additional Download Time Required
alpine-python	2	cbdbe7a5bc2a	2.81MB	486MB	23.4335s	-
		136e07eea1d6	38.92MB			
		f890c681a889	73.47MB			
alpine-python	3	1a5281d561d0	111.80MB		25.7491s	5.6346s

Table 18: Shared image layers with reduced size on disk and download times

7.8 Container Checkpoint and Restore

CRIU is an experimental feature of the container software used within this research. It can freeze a running container at a specific point in time and save its current state in a series of files to disk. The 'freeze' files are used to restore the container to the exact point it was initially frozen. In Table 19 below, each image was pulled from a centralised online repository. The download/pull times reflect the speed of the local network and Internet download speed.

Image	Version	Size	Image Pull	Container Start	Checkpoint Time	Restart Container
Ubuntu	14.04	197MB	17.7051s	1.2662s	1.9744s	1.6811s
Ubuntu	16.04	131MB	12.9395s	1.2401s	1.9647s	1.6444s
Ubuntu	18.04	63.3MB	8.7451s	0.9692s	1.8933s	1.3225s
Ubuntu	20:04	72.9MB	8.9199s	1.1970s	1.9202s	1.3336s

Table 19: CRIU test cases on several Ubuntu OS versions

The table shows that the difference between the smallest (18.04 version) and largest (14.04 version) sized images was 133.7MB, representing an increase of 211.21%. However, across all of the images, the time taken to start the container was within a range of 0.2657s.

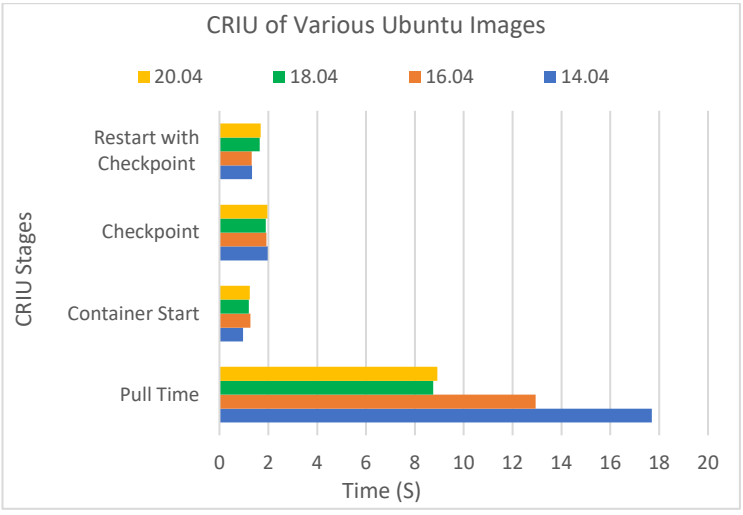


Chart 109: CRUI Stages and associated completion times

The time taken to checkpoint each container was similar, with a total variation between the quickest (18.04 version) and the slowest (14.04 version) being 0.0811s. The checkpoint process was the same regardless of container or image size. A checkpoint consists of several image files which include process information, file descriptors, process trees, memory and network state. To corroborate this typical checkpointing time frame, a checkpoint process was timed, utilising a small container (Linux alpine: distro) at 5.57MB and a larger container (Erlang: programming language) at 1.22GB in size. Both containers were checkpointed with the total checkpoint times recorded as:

- Alpine Linux checkpoint create time - 1.8727s.
- Elang checkpoint create time - 1.9775s.

Similar time frames were observed when the Ubunutu containers were restarted from the checkpoint. The checkpoint and restore times were consistent with an average checkpoint restore time frame of between 1.3 and 1.4 seconds. This again was verified with the Alpine and Erlang containers.

- Alpine Linux checkpoint restore time - 1.3202s.
- Elang checkpoint restore time - 1.3311s.

7.9 Chapter Summary

With each new vehicle model, more and more software are included, adding to the burden of addressing software-related problems. Automotive software update practices have followed the same vehicle recall procedure as when a physical component fails. However, the recall process incurs consumer inconvenience, system downtime, high monetary costs for the manufacturer and potentially reduced brand reputation and customer loyalty. The motor industry is attempting to address the limited available options regarding automotive software updates by utilising new automotive enabled connectivity.

To test the benefits of container-based software updating, several tests were conducted. Where new software was required during a test, the software was pulled from a central software repository hosted on the Internet. It is envisaged that any future software download would be conducted through automotive connectivity utilising a static or mobile-based communication network and the Internet, or a central repository which is either hosted with the vehicle manufacturer or third-party supplier.

The first test examined the benefits surrounding software update size and speed of download. To do this, two images (alpine-python2 and alpine-python3) were chosen, both of which shared a common OS, however, the application software within each image comprised of different versions. The test looked at the specific download and extract times for each image when downloaded independently. The total download and extract time for the two images was 54.8172s. The overall size on disk for the two images was recorded at 883MB. These results provide a baseline for a standard software version upgrade, which is similar to full binary re-flashing techniques. The second test used the same two images but utilised image layer sharing provided by the container software. There were similarities between the two images as they were both built using the same OS (alpine). As such, because both images shared two of the three image layers, the OS layers were not downloaded. This reduced the overall download time by 5.6346s, which was a 10.28% reduction in total download and extract time. Furthermore, when using container layer sharing, the overall storage requirement was reduced considerably by 397MB or 44.96% when compared with the first test.

The third test utilised a specific feature available to containers known as CRIU. Four versions (14.04, 16.04, 18.04 and 20.04) of the same Ubuntu OS were used, with each image ranging in size from 63-197MB. A container was created from each of these images. Although there was an increase of 211.21% in size between the largest and smallest image, each container's start time was within a range of 0.2657s. Regardless of image size, similar times were also observed during the checkpoint stage (a range of 0.0811s was observed) and the container restart (a range of 0.3586s was recorded). Regardless of image size, the average container start, checkpoint and restart times were 1.1681s, 1.9381s and 1.4954s, respectively. This test demonstrates that a container-based ECU, utilising CRIU, experiences an ECU function downtime of on average 1.5s, which is incompatible with real-time deadlines but is a technique that could apply to an online software update mode. It is also a potential technique that could be used in a DSU mode to update systems that are not responsible for safety-critical or real-time functions.

Container virtualisation is an ideal platform to facilitate OtA software updates. This research demonstrates that new software versions reflect changes within individual image layers, which result in shorter download times as well as minimising storage requirements. CRIU, although currently an experimental feature, has great promise in facilitating DSU where container downtime is approximately 1.5s. Container-based ECUs and OtA software update mechanisms can provide a constant level of updated software and patches over the vehicle's lifetime, installed independently of vehicle location. New software can be applied to the target system as and when required. The vehicle can remain secure through revised security software and patches when new vulnerabilities are discovered rather than waiting for it to be returned or the problem resolved during periodic maintenance intervals. This chapter has demonstrated that container-based software updates can be frequent and incremental. Consequently, the time taken to download and apply a configuration change or new software version is minimal compared with traditional full binary or delta ECU flashing.

Chapter 8 Conclusion

8.1 Research Summary

This research highlights several issues currently facing the automotive industry, many of which have arisen with system digitisation, and more recently, the introduction of ADAS and autonomous driving functions. Issues include increased weight, complexity and dependency on software, among others. Historically, vehicle manufacturers have generally responded to these problems by increasing the number of ECUs. This has inevitably led to larger amounts of automotive software and exacerbated problems associated with software-intensive systems, including bugs, errors and vulnerabilities within the code. However, automotive software is now regarded as a primary vehicle component, of similar importance to the engine when considering basic vehicle functionality. As such, the automotive industry has responded by proposing several different technologies to address the increasing number of ECUs and problems associated with this, such as SoC, FPGA and automotive domain controllers. Nevertheless, many of these potential technologies still rely on a hardware and software-based embedded device to provide automotive functionality. The research presented in this thesis moves away from these current practices and identifies many similarities between the datacentre and the automotive E/E architecture, arguing that virtualisation technologies, which have provided many benefits to the datacentre, can be replicated within an automotive context. Specifically, container virtualisation offers many advantages to the automotive E/E architecture. Notably, containerisation can promote ECU consolidation and in turn, reduce overall costs as well as enhance vehicle efficiency. It can also provide a robust mechanism to facilitate future software updates throughout the lifetime of a vehicle.

8.2 Key Findings

In order to demonstrate that containers are an effective means of supporting automotive software, a detailed study focusing on selected ECU's CPU and memory saturation and utilisation was conducted, utilising a custom research methodology. To test extensively container virtualisation within an automotive context, a standard automotive function was chosen. This automotive function was modelled on several small computing platforms with a similar hardware architecture to an automotive ECU. A number of peripheral input and output devices were incorporated as part of this automotive testbed. The test system was used as a hardware platform to investigate the specific resources required to support the automotive function when executing in two distinct test modes (native and container). The first test mode followed the standard practice of software running on dedicated hardware. In contrast, the second test mode encapsulated the software within a container and evaluated the additional resources required to support a container-based automotive function.

The results obtained from the CPU saturation tests demonstrate that there is a minimal increase in the number of waiting, running and additional processes invoked when executing in container mode. This increase is negligible and proves that the system is not over saturated. Whilst small spikes are observed when ECU functional software is initially started, the total additional CPU load in container execution is observed at only 6.73% across all triplets and ECUs. Similarly, the results obtained from the CPU utilisation tests across both native and container test modes reveal little variance.

CPU resources are scheduled between all active processes on the system. In terms of memory, resources are allocated per virtualisation instance, when that virtualisation instance starts. The more virtual instances that are in execution, the more memory that is required. The memory requirements of container operation are an important resource to observe because they determine how much additional memory is required to support each container-based function. The results obtained reveal that the average increase across all ECUs in required memory is approximately 13.07%. This is not excessive and equates in this series of tests to an overall average of 275kb of memory, which is approximately 68kb per container.

One aspect of this research concerns ECU consolidation, where container virtualisation is a significant facilitator. A number of load stress tests were conducted to understand the effects on resource saturation, utilisation and program performance. With CPU, memory and I/O stress loads applied individually and collectively, the container outperforms the native execution in almost all respects. The only way in which native performance can be increased to match container performance is by altering the priority of the process to the highest level. The results demonstrate that container operation, when excessive I/O load is applied, has a slightly detrimental effect on CPU saturation levels when compared with native execution. However, this is only observed during the *ldavg*-1 and 5 loads. Long term I/O load observed across the *ldavg*-15, shows that native and container CPU saturation are similar. This research highlights that program performance is impacted negatively to a greater degree when memory-bound processes are consolidated than when CPU bound processes are consolidated, however, this difference is minimal.

Finally, this research investigates the benefits of software update practices for container-based ECUs through a series of tests. It identifies three modes of software update relevant to a container-based ECU. The tests highlight the benefits of container image layers and how this particular architecture can support incremental software updates, as well as minimising individual container image footprints. The first series of tests show that any duplicated layers within a new image are not downloaded but are reused from the original stored image. They also demonstrate that under the same test conditions, where two similar images share the same OS layers, layer duplication reduces overall download time by approximately 10%, as well as saving almost 45% of additional storage space.

The second series of tests investigates how CRIU can be applied to container software updates. A single image with different versions and of varying sizes were used to understand how quickly these containers can be checkpointed and restored back to operation. CRIU enables running containers to store their current state in a series of files that can be restored at a later stage. This technology can facilitate a rapid software update procedure where the current state of a particular system or function must be preserved and then restored into a new or updated version of that software. The results of this series of tests show that regardless of container size, the checkpoint and restore times are very similar. These tests also highlight that the system downtime experienced during the CRIU process is approximately 1.5 seconds. Despite this

relatively short downtime, this time frame does not fall within real-time deadlines and safety-critical time frames. However, it is promising for any other system that does not require real-time or safety-critical operation.

In summary, this research demonstrates that containers do not have any significant detrimental impact on CPU memory and resources when running automotive software within a container. It also shows that either CPU bound or memory bound processes, or a combination of the two, are suited ideally for ECU consolidation when utilising container-based ECUs. Lastly, container virtualisation offers several benefits for automotive software updates -layer duplication is a key technique for reducing the time to download new updates, for minimising new software storage requirements and for facilitating OtA software updates throughout the vehicle's lifetime.

8.3 The Relevance of this Research

The findings from this research are of significance for both the automotive industry and industries that utilise embedded systems, more broadly. Firstly, the research demonstrates that multiple ECU functionality can be incorporated into individual containers on a single hardware platform, thus consolidating individual bespoke embedded hardware and associated software. This results in a reduction of both physical hardware and overall weight, which has a direct positive impact on the fuel economy and operational range of the vehicle. Furthermore, containers offer several significant cost-savings to the automotive industry. For example, savings can be achieved through a reduction in hardware development costs – this could have a substantial impact when considering that costs related to bespoke ECU hardware development have increased by 75% since 2000 and are expected to double by 2030. Savings can also be realised through a reduction in individual ECU hardware components. In addition, by reducing costs for the manufacturer, savings can be passed onto the consumer.

Secondly, the research shows that container-based ECUs can promote automotive software updates, particularly OtA software updates in conjunction with vehicle connectivity. This can reduce significantly the need to recall vehicles when encountering a software-related problem because the new software can be deployed to a target vehicle remotely, as and when required. Notably, by utilising containers in this way,

overall vehicle security can be maintained and any potential software vulnerabilities can be addressed. This has significant implications for the automotive industry. The number of vehicles recalls in the U.S. associated with a software fault has risen dramatically by 1400% since 2010. Vehicle recalls are highly disruptive to the consumer, expensive for the manufacturer and can, in some cases, reduce brand reputation. It is estimated that resolving a software-related error post-sale is 30 times more expensive than compared with fixing the same issue during the early stages of the SDLC. Compounding this, the current automotive software update practices and procedures are not keeping pace with the rapid increase in the number of lines of software code. The research findings demonstrate that these problems may be overcome by utilising container-based ECUs, whereby errors, bugs and vulnerabilities can not only be addressed promptly and effectively, but also throughout the vehicle's lifetime. Additionally, container-based OtA software updates can significantly reduce disruption to consumers. Consumers are also able to incorporate additional or new functionality into a container-based ECU, which can generate additional revenue for the manufacturer in terms of their aftermarket sales.

Lastly, the findings from this research have relevance for non-automotive industries that utilise embedded systems. Although this research's primary focus is the automotive E/E architecture, the technologies and techniques researched can be applied to a number of different applications. For example, any functionality which requires embedded systems could benefit from container virtualisation. Virtualisation technology is currently employed in Industrial automation and manufacturing, especially in Industry 4.0. Container virtualisation can aid embedded technology within industrial machine controlling and monitoring. They can be deployed within industrial manufacturing systems and supply-chain process to promote efficiency. Production lines that require minimal downtime could benefit from the container-based software update mechanisms presented within this research. Containers can hugely benefit the Internet of Things (IoT) devices which are typically small, low-cost single-board devices where connectivity and functionality have to be finely balanced with power consumption.

8.4 Future Work

This research focuses on the specific resources required to support an automotive function utilising container within the automotive E/E architecture. There are opportunities to utilise this new research methodology, and this section explores the following areas the current research which can be taken forward.

8.4.1 Optimised container and OS configurations

This research uses standard versions of ECU OS as well as container software. These ensure the functionality of the container software as well as enabling the installation of various software monitoring tools. Both native and container test modes within this research utilise the same hardware and software. To advance this research, the generic hardware and software could be developed from a number of potential optimised OS and container platforms, which would enable a more optimised and efficient container-based ECU specifically through kernel scheduling algorithms. This could potentially reduce overall resource use, further improving and enhancing ECU consolidation by accommodating more containers per hardware platform.

8.4.2 Automotive security and container-based ECUs

Various aspects of security are investigated briefly as part of this research. A more detailed study concerning the security of container-based ECUs within the automotive E/E architecture is required. Container virtualisation is not as secure as full system virtualisation because isolation is provided within the OS kernel rather than through separate virtual machines. However, because containers have a much smaller trusted computer base, they would benefit from further investigation. There are also opportunities to investigate further the security aspects of OtA software updates, particularly regarding the accuracy of received updates as well as verification and validation of any potential new software update.

8.4.3 Container-based ECUs and associated power consumption

Increased ECU power consumption within the automotive E/E architecture can increase fuel consumption and reduce both vehicle performance and operational range. The hardware selected for this research had limited functionality to monitor and analyse overall power consumption. However, the hardware selected had similar power consumption rates to larger ECU systems found within the automotive E/E architecture. Future research could assess the effect on overall power consumption by consolidating ECUs into fewer container-based ECU platforms. This may also provide potential benefits for extending the operational range of electric vehicles.

8.4.4 Networking

ECU consolidation reduces the requirement for inter-ECU communication via a physical in-vehicle network. Whilst this was not a focus of the current research, it has the potential to reduce the requirement for physical network media, which can reduce associated hardware, weight and complexity. Future studies could explore and evaluate data transfer rates and associated benefits of container-based virtual networks.

8.4.5 Software updates, CRIU and real-time

Notably, this research provides a standard mechanism of automotive software update utilising container-based ECUs. Across several tests, this method of software update was corroborated. Three modes of software update were proposed within this research, which utilised vehicle connectivity and OtA techniques. Additional research regarding both of these techniques, in terms of how they interact and the security mechanisms required to provide a safe and robust update procedure, is required. Furthermore, studies could explore open-source CRIU software and how it could be optimised to reduce the checkpoint and restore procedure from seconds to milliseconds. This would then fall within real-time deadlines, providing a true DSU technique.

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Appendices

Appendix A Software Tools

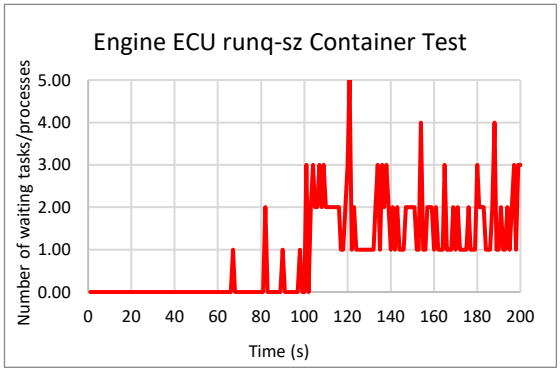
Test Case	System Resource	Software Tool	version	Sample rates	Example Tool Configuration	Observed Metric	Metric Reference
System	Memory	*sar*	11.4.3	1 second	sar -B 1 5	majflt/s	Major faults per second
						faults/s	Total page faults per second
					sar -W 1 5	pswpin/s	No. of swap pages/s
						pswout/s	No. of swap pages the system brought out per second
					sar -r 1 5	%memused	total memory used
					sar -R 1 5	frmpg/s	Memory frame pages per second
						bufpg/s	Buffer pages per second
						capmg/s	Cache pages per second
		ps	3.3.10	-	ps -eo min_flt,maj_flt	min_flt	Minor page faults
		free	3.3.12	0.1 seconds	free -m	used	Used memory (total-free-buffers-cache)
						free	Free memory
		vmstat	3.3.12	1 second	vmstat 1	si	Memory swapped in from disk
						so	Memory swapped out from disk
						swpd	The amount of virtual memory used
						free	The amount of idle memory
		sar	11.4.3	1 second	sar -B 1 5	pgscank/s	No. of pages scanned by the kswapd daemon/s
						pgscand/s	No. of pages scanned/s
		smem	-	-	smem -tu / smem -tw	USS	Unique set size memory

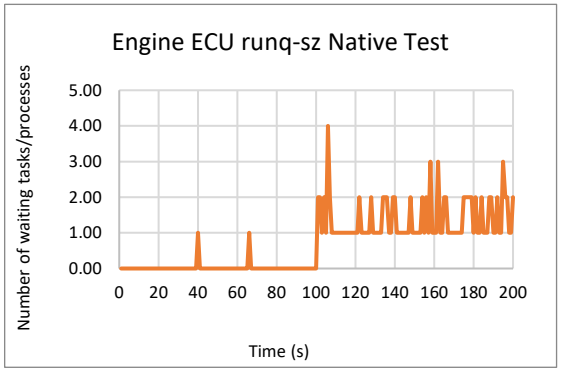
Test Case	System Resource	Software Tool	version	Sample Rates	Example Tool Configuration	Observed Metric	Metric Reference
System	CPU	*vmstat*	3.3.12	1 Second	vmstat 1	R state	No. processes waiting runtime
						D state	No. processes in sleep
						us	% ALL CPU user processes
						sy	% ALL CPU system processes
		sar	11.4.3	1 Second	sar -q 1 5	*ldavg*-1/5/15	load average 1/5/15 min
						runq-sz	No. of tasks awaiting runtime
						plist-sz	No. of tasks in the task list
					sar -u 1 5	%user	CPU time per user processes
						%system	CPU time per system processes
					sar -w 1 5	cswch/s	Context switches per second
		perf	4.9.82	250 samples/s	perf stat	context-switches	Total number over a sample time period

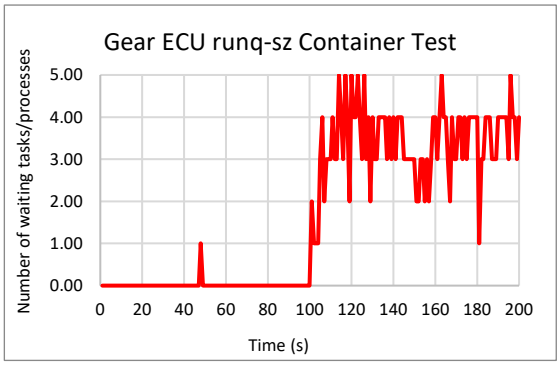
Test Case	System Resource	Software Tool	version	Sample Rate	Example Tool Configuration	Observed Metric	Metric Reference
Per process	Memory	*cat*	8.25	-	cat /proc/<pid>/stat | awk '{print $10}	min_flt	minor faults
		pmap	3.3.12	-	pmap -x <pid>	kbytes	Process memory map Size of map in Kb
		sar	11.4.3	1 second	sar -B 1	fault/s majflt/s	Total and major faults per second
		smem	-	-	smem -tu / smem -tw	USS	Unique set size memory
	CPU	*cat*	8.25	-	cat /proc/<pid>/schedstat	time	Time spent on CPU Time spent waiting on the queue
		perf	4.9.82	250 samples/s	perf sched record -- sleep 1 perf sched latency	runtime Max. delay	Avg. and max. delay per schedule
		sar	11.4.3	1 second	sar -P ALL 1 5	%user	% per CPU user processes
						%system	% per CPU system processes
						%idle	% per CPU idle time
		pmap	3.3.12	-	pmap <pid> | tail -n 1	kb	total memory use
		tiptop	2.3	0.5 second	tiptop -H -K	IPC	Instructions per cycle
		perf	4.9.82	250 samples/s	perf stat		

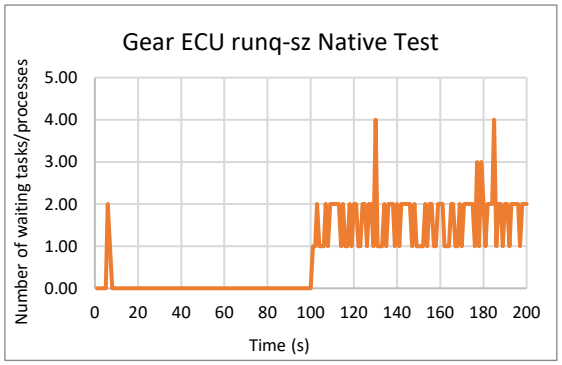
Test Case	System Resource	Software Tool	version	Sample rates	Example Tool Configuration	Observed Metric	Metric Reference
All cases	Memory	*top*	3.3.12	0.5 seconds	Various switches and display outputs	Memory CPU	Collaboration and general tool
	CPU	*htop*	2.0.2	0.5 seconds			
		nmon	14g	1 second			

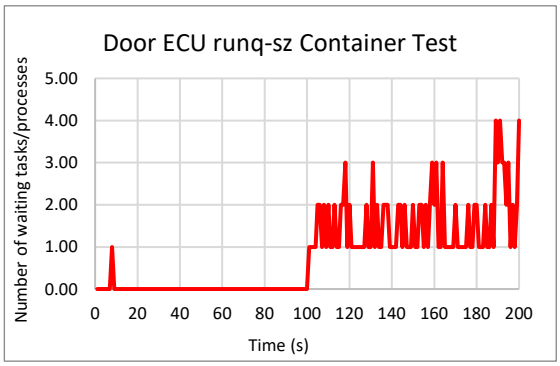
Appendix B Individual ECU *runq-sz* Results

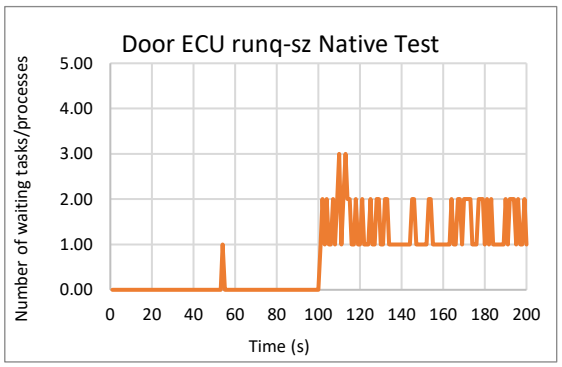


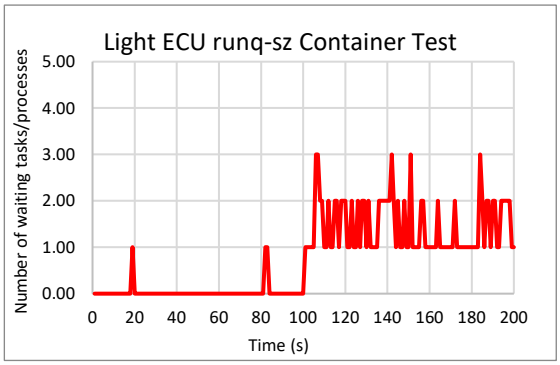


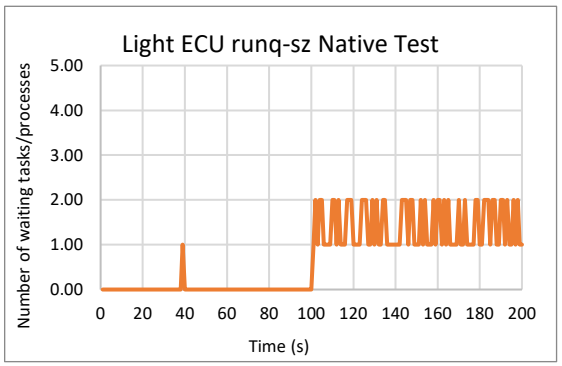




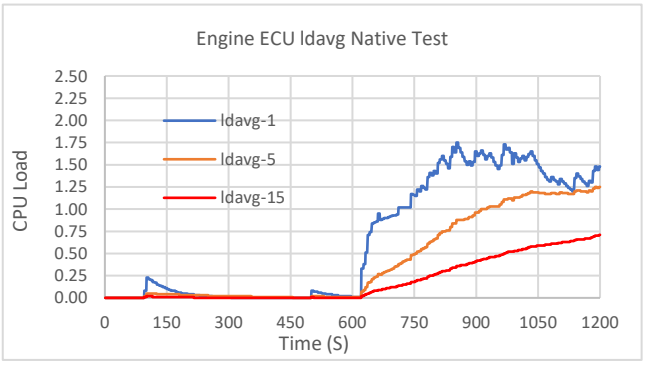




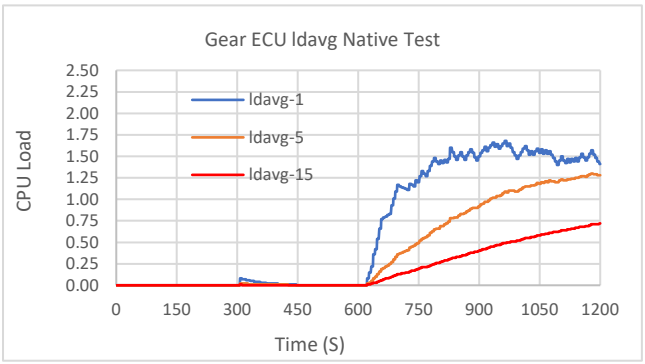




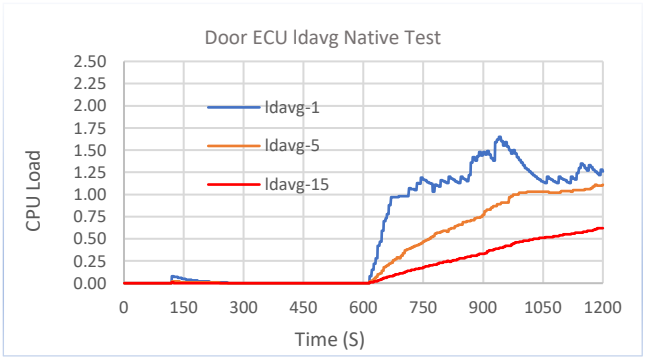
Appendix C Individual ECU *ldavg* Results



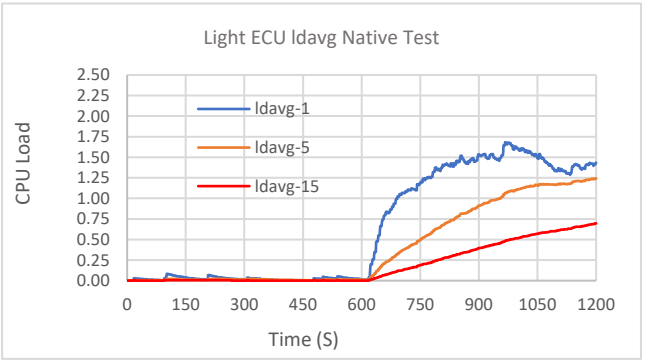
Engine ECU *ldavg* (4 Cores)			
ldavg-n	Minimum	Maximum	Average
ldavg-1	0	1.72	0.66
ldavg-5	0.08	1.24	0.42
ldavg-15	0.02	0.71	0.19



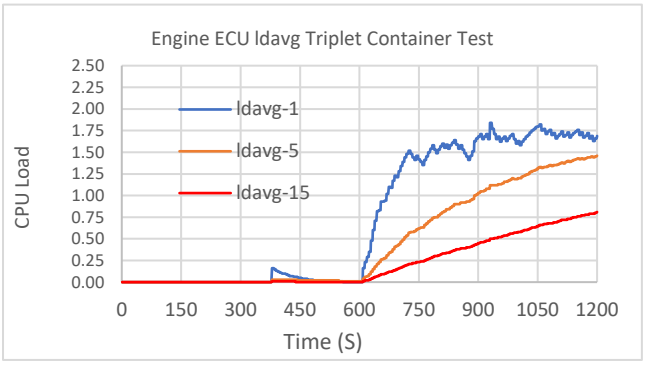
Gear ECU *ldavg* (4 Cores)			
ldavg-n	Minimum	Maximum	Average
ldavg-1	0	1.68	0.66
ldavg-5	0.08	1.30	0.41
ldavg-15	0.02	0.71	0.19



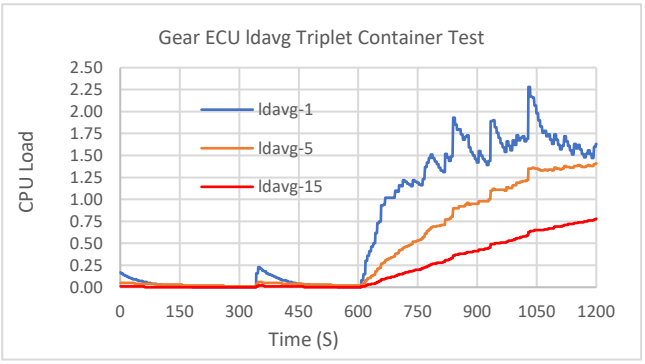
Door ECU *ldavg* (4 Cores)			
Ldavg-n	Minimum	Maximum	Average
ldavg-1	0.03	1.65	0.57
ldavg-5	0.01	1.11	0.36
ldavg-15	0	0.62	0.17



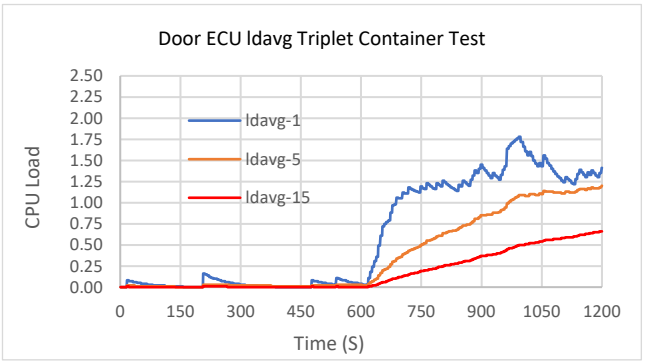
Light ECU *ldavg* (4 Cores)			
Ldavg-n	Minimum	Maximum	Average
ldavg-1	0	1.68	0.65
ldavg-5	0.57	1.01	0.41
ldavg-15	0.23	0.83	0.19



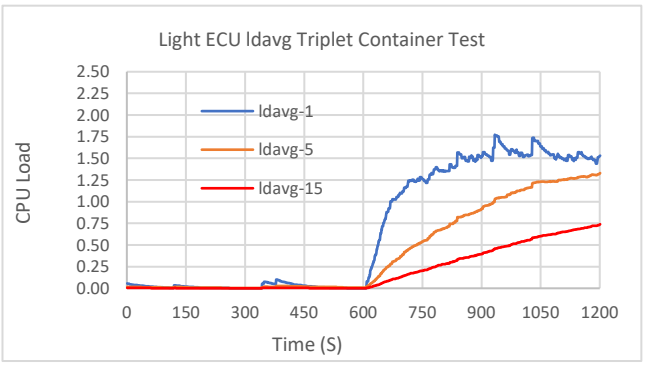
Engine ECU *ldavg* (4 Cores)			
ldavg-n	Minimum	Maximum	Average
ldavg-1	0	1.84	0.74
ldavg-5	0.01	1.46	0.48
ldavg-15	0	0.81	0.22



Gear ECU *ldavg* (4 Cores)			
ldavg-n	Minimum	Maximum	Average
ldavg-1	0	2.28	0.73
ldavg-5	0.01	1.41	0.46
ldavg-15	0	0.78	0.21

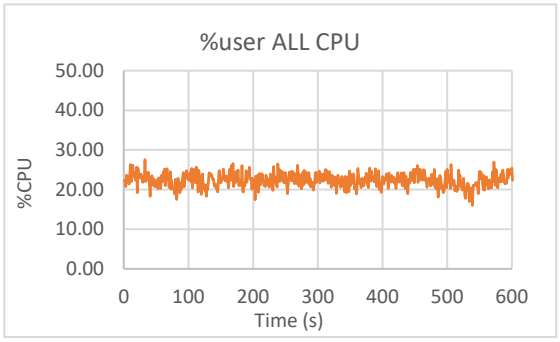


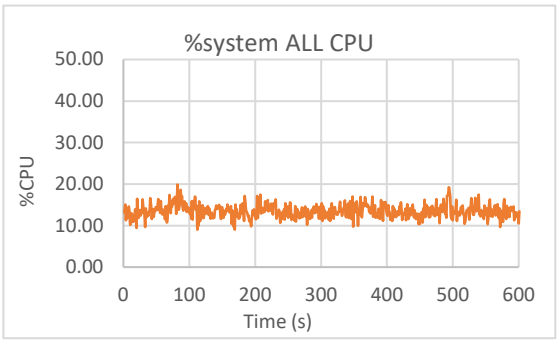
Door ECU *ldavg* (4 Cores)			
ldavg-n	Minimum	Maximum	Average
ldavg-1	0.03	1.78	0.62
ldavg-5	0.02	1.2	0.39
ldavg-15	0	0.66	0.18

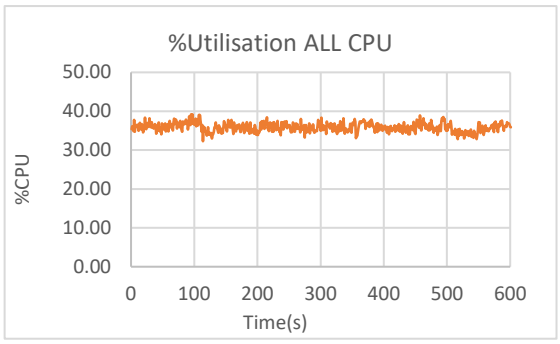


Light ECU *ldavg* (4 Cores)			
ldavg-n	Minimum	Maximum	Average
ldavg-1	0	1.77	0.68
ldavg-5	0	1.33	0.43
ldavg-15	0	0.74	0.20

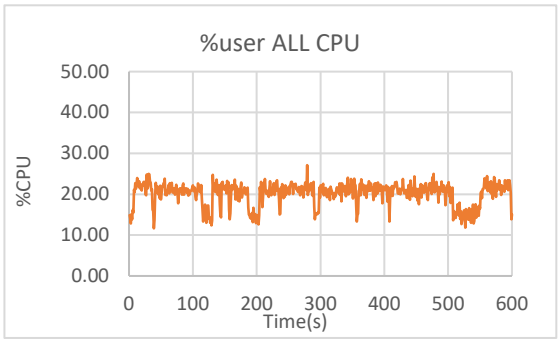
Appendix D ECU CPU Utilisation Tests

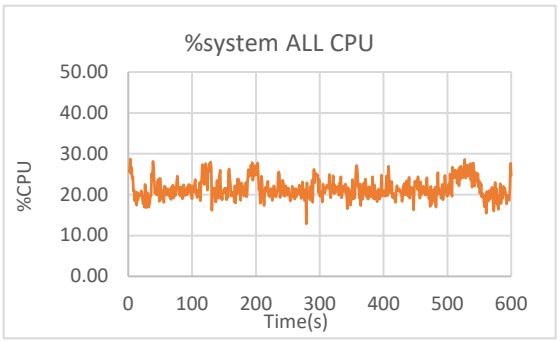


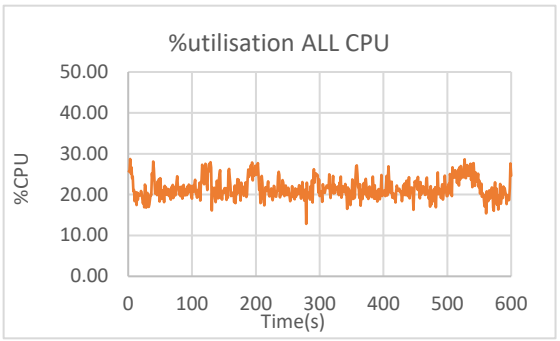




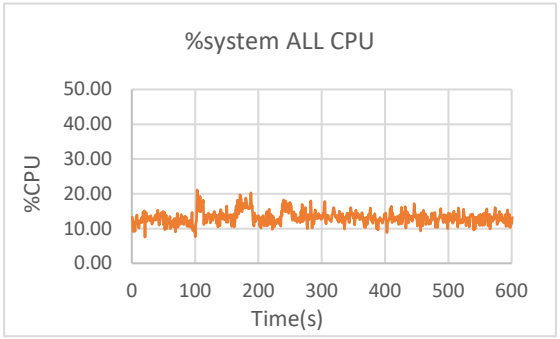
Native CPU Utilisation			
Engine ECU	Min	Max	Average
%user	16.01%	27.54%	22.41%
%system	9.04%	19.88%	13.51%
%utilisation	32.29%	39.19%	35.91%

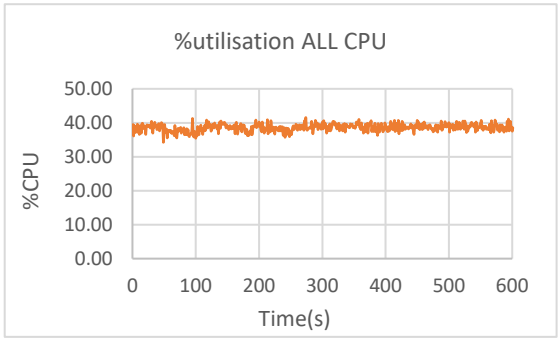




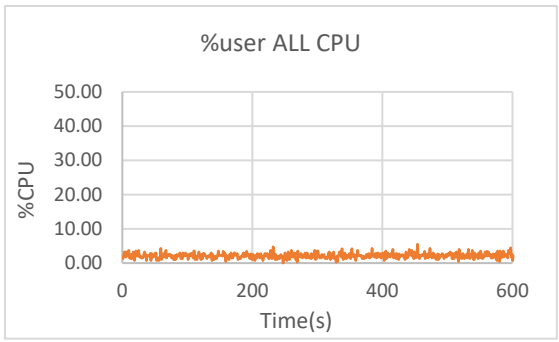


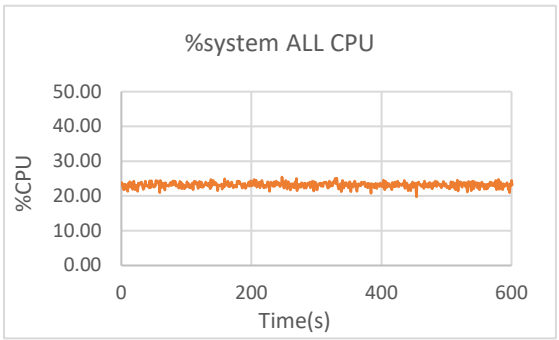
Native CPU Utilisation			
Door ECU	Min	Max	Average
%user	11.65%	27.11%	20.11%
%system	12.83%	28.81%	21.54%
%utilisation	38.28%	44.66%	41.66%

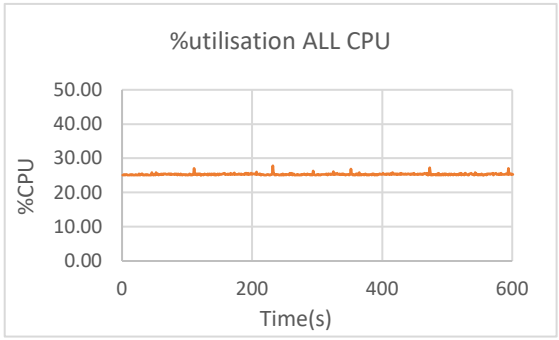




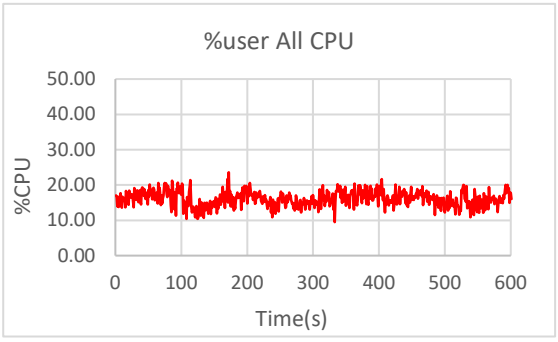
Native CPU Utilisation			
Gear ECU	Min	Max	Average
%user	17.81%	29.57%	25.46%
%system	7.55%	21.10%	13.16%
%utilisation	34.24%	41.55%	38.62%

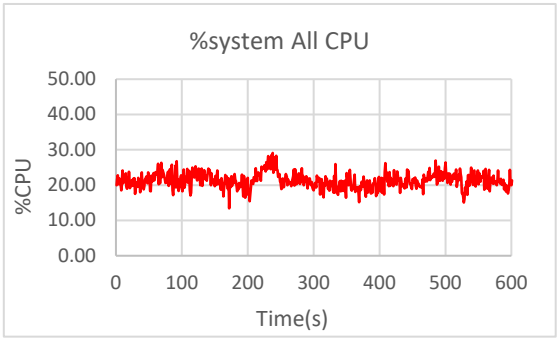


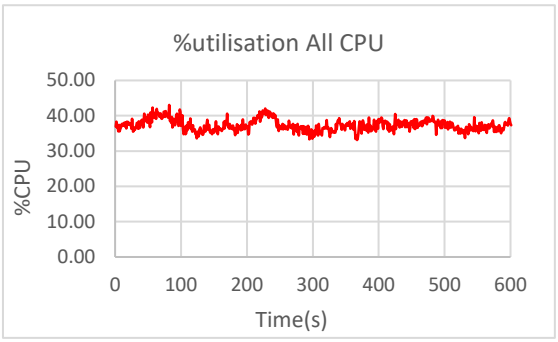




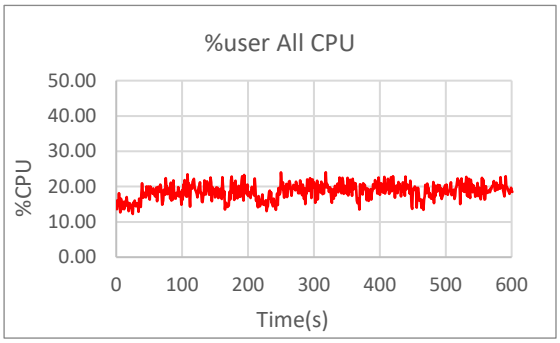
CPU Utilisation			
Light ECU	Min	Max	Average
%user	0.25%	5.0%	2.27%
%system	20.25%	25.06%	22.96%
%utilisation	25.0%	27.50%	25.23%

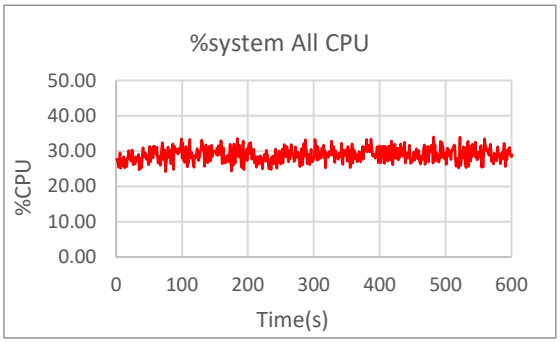


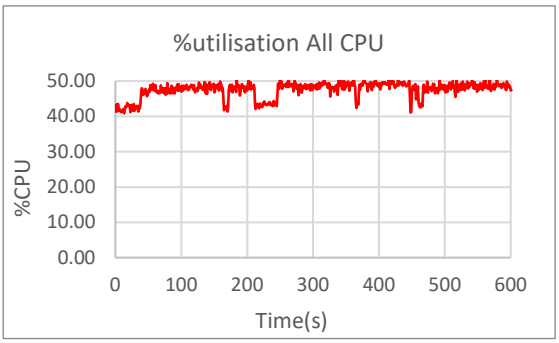




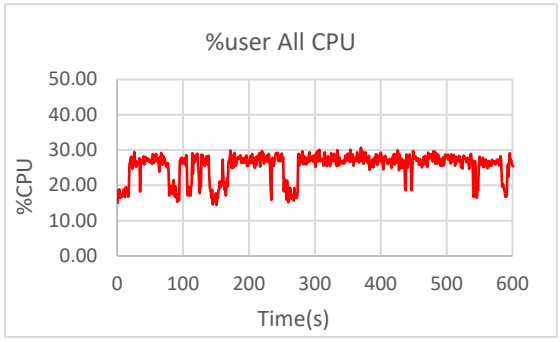
CPU Utilisation			
Light ECU	Min	Max	Average
%user	9.50%	23.58%	16.06%
%system	13.43%	29.11%	21.30%
%utilisation	33.14%	43.05%	37.37%

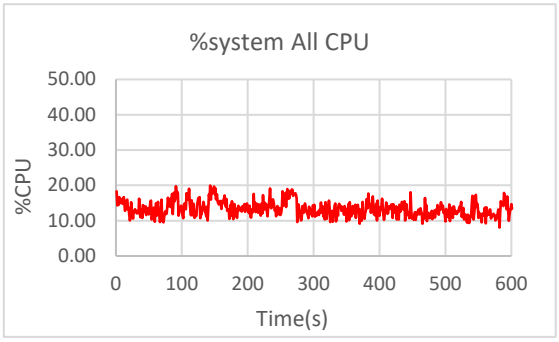


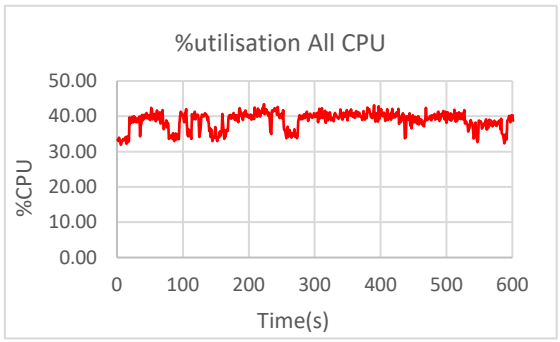




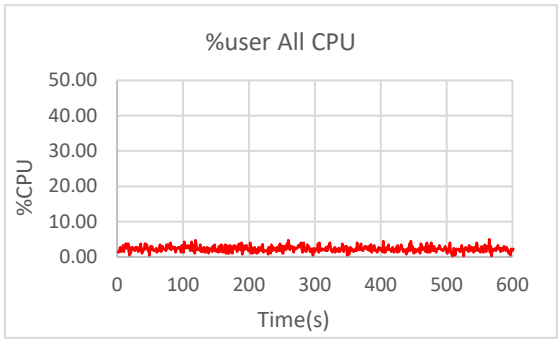
CPU Utilisation			
Light ECU	Min	Max	Average
%user	12.24%	24.05%	18.60%
%system	24.17%	34.01%	29.01%
%utilisation	40.85%	51.55%	47.61%

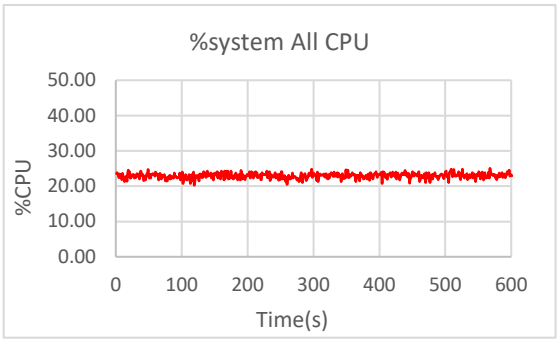


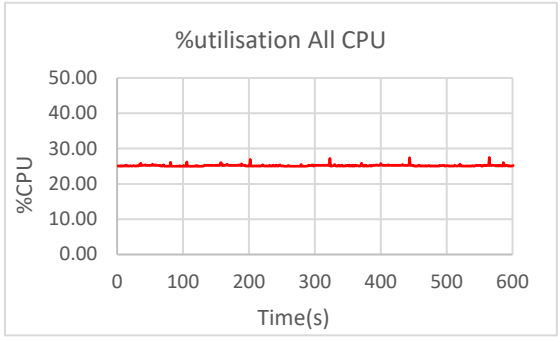




CPU Utilisation			
Light ECU	Min	Max	Average
%user	14.45%	30.67%	25.49%
%system	8.07%	19.95%	13.36%
%utilisation	31.94%	43.44%	38.85%







CPU Utilisation			
Light ECU	Min	Max	Average
%user	0.75%	5.50%	2.14%
%system	19.75%	25.44%	23.20%
%utilisation	25.00%	27.82%	25.35%

Appendix E 1st Prize DMU Research Poster Competition

Containerisation: A Mechanism to Provide Seamless Automotive Software Updates

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DE MONTFORT UNIVERSITY LEICESTER

Introduction

The modern motor car is one of the most complex systems we use in our day to day lives. This complexity comes from the increasing use of computing technology known as electronic control units (ECUs) (fig.1).

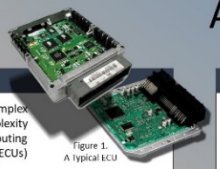
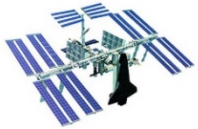


Figure 1. A Typical ECU

In many vehicle models there are in excess of 100 ECUs which monitor and control a wide range of software based functions. As more functions are incorporated into the car it inevitably increases the requirement for more computer hardware. This rise in amount of hardware results in even more software.

~100 Million lines of software code

In fact the modern motor car requires 50X more software to operate than the ISS making it one of the most complex machines in use in our daily lives

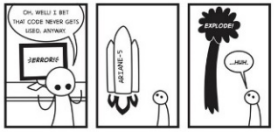


~2 Million lines of software code

The problem with software

Unfortunately **ALL** software contains errors or bugs which arise from mistakes made in a programs source code often during the design and coding process.

Bugs in software have been attributed to cause financial loss, for example in 2016 software bugs cost the United States economy $1.1 trillion [1]. Software bugs have also been responsible for catastrophic failures such as the prototype Ariane 5 rocket which was destroyed due to a small software bug in its on-board guidance program [2].



How are bugs fixed in automotive software?

Software is now a critical component of the modern motor car, but, all software code is vulnerable to errors which when discovered must be addressed. If software errors are not addressed they may expose the manufacturer to liability if something goes wrong due to an inherent flaw in their software. Once a flaw has been discovered and rectified that new, updated code needs to be deployed and installed to the target vehicle.

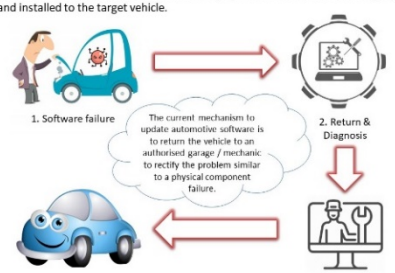


Figure 3. Current Automotive Software Update mechanism

Fig. 3 shows the current mechanism for automotive software updates. This mode of repair is disruptive to the consumer in time and convenience and expensive to the manufacturer in cost of repair and brand reputation. To address the current issues surrounding the automotive software update process a new automated solution is required.

Research: A new virtual automotive architecture

Through the sheer amount of on-board software and data a vehicle generates in its normal mode of operation the traditional motor car has shifted towards becoming a mobile datacentre. The traditional datacentre relied on individual and often underutilised servers dedicated to a particular role or task within an organisation. Typically as new tasks and roles were introduced new dedicated hardware and software was installed. This situation is being replicated within the automotive architecture.

My research identified virtualisation as a key technology in the datacentre which has had considerable impact in reducing the need for individual hardware and improving software management and regular periodic updates. This virtualisation technology can have a similar impact on the encumbered automotive architecture.

To meet the challenges of increasing automotive software and simplify and automate the software update mechanism my research utilises a specific type of virtualisation: operating system virtualisation also known as the container. A container based automotive architecture could address these challenges through centralising where software is stored within the car.

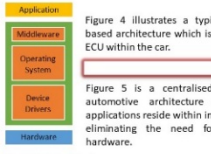


Figure 4 illustrates a typical dispersed ECU based architecture which is repeated for every ECU within the car.

Figure 5 is a centralised container based automotive architecture where individual applications reside within individual containers eliminating the need for individual ECU hardware.

Fig. 4 Typical ECU Architecture

Fig. 5 Container Based Architecture

Proposed mechanism for automotive software updates

A container based automotive architecture can utilise a vehicles connectivity through the 4G mobile network to inform and deploy a software patch or new updated software functionality as shown in Figure 6. This is done without vehicle downtime or disruption to the consumer.

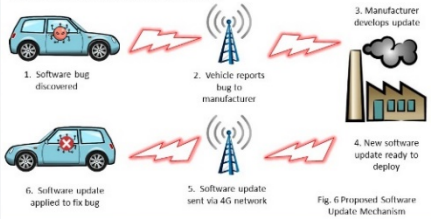


Fig. 6 Proposed Software Update Mechanism

Summary

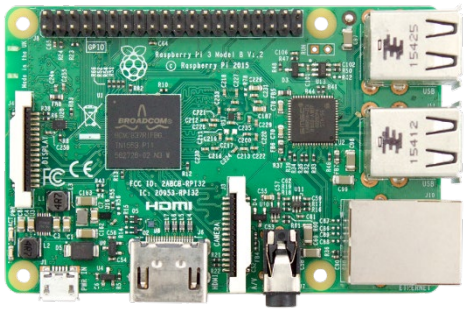
To prove the concept and case for a container based automotive architecture the main focus of this research is to examine overall system latency. A test clustered computer system has been designed and built to investigate and measure a number of key areas, these include:

- Overall system latency
  - Under load (full system operation – car driving at speed)
  - Idle (minimal system operation – car in idle)
- Program / application latency
  - Individual services
- Vehicle network latency
  - Speed of data transfer between single and clustered containers

[1] R. Choane, "Financial Cost of Software Bugs," Medium, 16 November 2017. [Online]. Available: https://medium.com/@ryancohane/financial-cost-of-software-bugs-51b4d193f107. [Accessed 2 February 2019].
[2] J. L. Lions, "ARIANE 5 Flight 501 Failure Report by the Inquiry Board," 19 July 1996. [Online]. Available: http://sunnyday.mit.edu/nasa-class/Ariane5-report.html. [Accessed 19 February 2019]

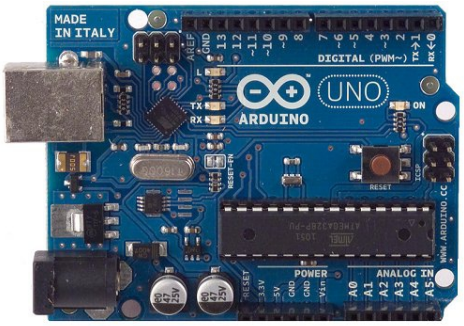
Appendix F Automotive Testbed Hardware

Raspberry Pi Model B+ Technical Specifications



- Broadcom BCM2837 64bit ARMv7 1.2GHz Quad Core Processor
- 1GB RAM
- BCM43143 Wi-Fi on board
- Bluetooth Low Energy (BLE) on board
- 40pin extended GPIO
- 4 x USB 2 ports
- 4 pole Stereo output and Composite video port
- Full size HDMI
- Micro SD port - operating system and storing data
- Micro USB power source (supports up to 2.4 Amps)

Arduino Uno Specification



- Microcontroller: ATmega328P
- Operating Voltage: 5V
- Input Voltage (recommended): 7-12V
- In/out Voltage (limit): 6-20V
- Digital I/O Pins: 14
- PWM Digital I/O Pins: 6
- Analog Input Pins: 6
- Flash Memory: 32 KB (ATmega328P) of which 0.5 KB used by bootloader
- SRAM: 2 KB (ATmega328P)
- EEPROM: 1 KB (ATmega328P)
- Clock Speed: 16 MHz

Door ECU

```
#!/usr/bin/env python
import RPi.GPIO as GPIO
from time import sleep
import threading
import time
import sys
import socket
import serial

ser = serial.Serial('/dev/ttyUSB0', 9600)
ser.flushInput()
door_state = 0

##USEFUL FUNCTIONS
def bytes_to_int(bytes):
     result = 0
     for b in bytes:
          result = result * 256 + int(b)
     return result


##DEFINITION OF SOCKETS
#port for doors' lights
TCP_IP = "192.168.1.170"
TCP_PORT = 40069
BUFFER_SIZE = 20

#port for gears
UDP_IPg = ""
UDP_PORTg = 40010
sockg = socket.socket(socket.AF_INET, socket.SOCK_DGRAM)
# for UDP
sockg.bind((UDP_IPg, UDP_PORTg))

#port for speed
UDP_IPs = ""
UDP_PORTs = 40011
socks = socket.socket(socket.AF_INET, socket.SOCK_DGRAM)
# for UDP
socks.bind((UDP_IPs, UDP_PORTs))


##FUNCTIONS
def setup():
     GPIO.setwarnings(False)
```

```
      GPIO.setmode(GPIO.BCM)
# Use board pin numbering
      GPIO.setup(18, GPIO.IN, pull_up_down=GPIO.PUD_DOWN)

# Set GPIO 18 to be an input pin and set initial value to be
pulled low (off)
      GPIO.setup(6, GPIO.OUT)
      GPIO.setup(13, GPIO.OUT)
      GPIO.setup(19, GPIO.OUT)
      GPIO.setup(26, GPIO.OUT)

#functions to close/open doors
def closeAll():
      GPIO.output(6, GPIO.LOW)
      GPIO.output(13, GPIO.LOW)
      GPIO.output(19, GPIO.LOW)
      GPIO.output(26, GPIO.LOW)

def openAll():
      GPIO.output(6, GPIO.HIGH)
      GPIO.output(13, GPIO.HIGH)
      GPIO.output(19, GPIO.HIGH)
      GPIO.output(26, GPIO.HIGH)

def openDriver():
    GPIO.output(6, GPIO.HIGH)

#functions to send info to lights ECU - remote
def swLed1(ev=None):  # DOORS LOCK
      print ('All Doors Locked')
# This not required in main program
      s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
      s.connect((TCP_IP, TCP_PORT))
      s.sendall(b'1')
      s.shutdown(socket.SHUT_RDWR)
      s.close()
      closeAll()
      sleep(0.2)

def swLed2(ev=None): # DOORS UNLOCK
      print ('All Doors Unlocked')
# This not required in main program
      s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
      s.connect((TCP_IP, TCP_PORT))
      s.sendall(b'2')
      s.shutdown(socket.SHUT_RDWR)
      s.close()
      openAll()
      sleep(0.2)

def swLed3(ev=None): # DRÃ©IVERS DOOR UNLOCK
      print ('Drivers Door Unlocked')
# This not required in main program
```

```
      s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
      s.connect((TCP_IP, TCP_PORT))
      s.sendall(b'3')
      s.shutdown(socket.SHUT_RDWR)
      s.close()
      openDriver()
      sleep(0.2)


##FUNCTIONS FOR THREADS
#function to get gears from socka
def connectGear(socka):
      global gear
      closed=False
      gear=0
      lastGear=0
      while True :
            data, addr = socka.recvfrom(1024)
            gear=bytes_to_int(data)
            #print("gear : " + str(gear) + "lastGear : " +
str(lastGear) +" speed : " + str(valKMH) + " flag :" +
str(flag))
            if(not closed and (gear==3 or valKMH>40)) :
                  closeAll()
                  closed=True
                  print("speed or gears too high, doors locked",
flush=True)      # DOORS LOCK


            if(closed and (lastGear==1 and gear==0)) :
                  openAll()
                  closed=False
                  print("neutral mode, doors unlocked",
flush=True)
# DOORS UNLOCK

            if(GPIO.input(18)==True):
                  openAll()
                  closed=True
                  print("          -----EMERGENCY-----   ",
flush=True)
            lastGear=gear

#function to get speed from socka
def connectSpeed(socka):
    #gear has to be global to be used in another thread
    global valKMH
    while True :
             data, addr = socka.recvfrom(1024)
             valKMH=bytes_to_int(data)

#function to send remote input to socka
def sendLights():
```

```
    while True:
        if(ser.inWaiting()>0 and (gear==0)):
# Serial waiting for input
            inputValue = ser.read(1)
# Read incoming serial data
            if(inputValue  == b'o'):
                swLed1()
            elif(inputValue == b'O'):
                swLed2()
            elif(inputValue == b'='):
                swLed3()
##DESTROY
def destroy(socka):
        socka.close()

##MAIN
if __name__ == '__main__':
        #defining the threads
        t1 = threading.Thread(target=connectGear, args=(sockg,
))
        t2 = threading.Thread(target=connectSpeed, args=(socks,
))
        t3 = threading.Thread(target=sendLights, args=())

        setup()

        try:
                t1.daemon=True
                t2.daemon=True
                t3.daemon=True
                t2.start()
                t1.start()
                t3.start()
                while True: time.sleep(100)

        except KeyboardInterrupt: # When 'Ctrl+C' is pressed,
the child program destroy() will be executed.
                destroy(sockg)
                destroy(socks)
                sys.exit()
```

```
#!/usr/bin/env python


# coding: utf8
import sys
import socket
import threading
import time
from time import sleep

# USEFUL FUNCTION
# to translate int to bytes

def int_to_bytes(value, length):
    result = []
    for i in range(0, length):
        result.append(value >> (i * 8) & 0xff)
    result.reverse()
    return result

# DEFINITION OF SOCKETS
# to get gears from arduino
UDP_IP = ""
UDP_PORT = 40004
sock = socket.socket(socket.AF_INET,  # for Internet
                     socket.SOCK_DGRAM)  # for UDP
sock.bind((UDP_IP, UDP_PORT))

# to send gears to speed2
UDP_IP_send = "192.168.1.160"
UDP_PORT_send = 40009
socksend = socket.socket(socket.AF_INET,  # for Internet
                         socket.SOCK_DGRAM)  # for UDP

# to send to door lock
UDP_IP_sendlock = "192.168.1.140"
UDP_PORT_sendlock = 40010
socksendlock = socket.socket(socket.AF_INET,  # for Internet
                             socket.SOCK_DGRAM)  # for UDP

# FUNCTIONS FOR THREADS
# function to connect to Arduino and process gears

def connectGear(socka):
        # gear has to be global to be used in another thread
    global gear
    gear = 0
    lastgear = 0
```

```
    while True:
        data, addr = socka.recvfrom(1024)  # length of the
buffer : 1024 bytes
        downShiftButton = data[0]
        upShiftButton = data[1]
        if((upShiftButton) == 1 and downShiftButton == 0 and
lastGear == 0):
            if(gear < 5):
                gear = gear + 1
                lastGear = 1
        elif((downShiftButton) == 1 and (upShiftButton) == 0 and
lastGear == 0):
            if(gear > 0):
                gear = gear - 1
                lastGear = 1
        else:
            gear = gear

        if(downShiftButton == 1 or (upShiftButton) == 1):
            lastGear = 1
        else:
            lastGear = 0

# function to send gears to socka

def sendGear(socka, IP, PORT):
    while True:
        gearbytes = bytes(int_to_bytes(gear, 1))
        socka.sendto(gearbytes, (IP, PORT))

# DESTROY
def destroy(socka):
    socka.close()

# MAIN
if __name__ == '__main__':
    # defining the threads
    t1 = threading.Thread(target=connectGear, args=(sock, ))
    t2 = threading.Thread(
        target=sendGear, args=(socksend, UDP_IP_send,
UDP_PORT_send,))
    t3 = threading.Thread(target=sendGear, args=(
        socksendlock, UDP_IP_sendlock, UDP_PORT_sendlock,))

    try:
        t1.daemon = True
        t2.daemon = True
        t3.daemon = True
        t1.start()
        t2.start()
        t3.start()
        while True:
            time.sleep(100)
```

```
    except KeyboardInterrupt:  # When 'Ctrl+C' is pressed, the
child program destroy() will be  executed.
        print("-----QUITTING-----")
        destroy(sock)
        destroy(socksend)
        destroy(socksendlock)
        sys.exit()
```

Engine ECU

```
#!/usr/bin/env python
# coding: utf8
import sys
import socket
import time
import threading
from time import sleep
from datetime import datetime

##USEFUL FUNCTIONS
#definition of the function for mapping a range values to
another
def translate(value, inputMin, inputMax, outputMin, outputMax):
    # Figure out how 'wide' each range is
    inputSpan = inputMax - inputMin
    outputSpan = outputMax - outputMin

    # Convert the input range into a 0-1 range (float)
    valueScaled = float(value - inputMin) / float(inputSpan)

    # Convert the 0-1 range into a value in the output range.
    return outputMin + (valueScaled * outputSpan)

#to  translate bytes into int
def bytes_to_int(bytes):
    result = 0
    for b in bytes:
           result = result * 256 + int(b)
    return result

def int_to_bytes(value, length):
        result = []
        for i in range(0, length):
                result.append(value >> (i * 8) & 0xff)
        result.reverse()
        return result

##DEFINITION OF SOCKETS
```

```
# Port to get gears
UDP_IPg = ""
UDP_PORTg = 40009

sockg = socket.socket(socket.AF_INET, # for Internet
                      socket.SOCK_DGRAM) # for UDP
sockg.bind((UDP_IPg, UDP_PORTg))

# Port to get speed from Arduino
UDP_IPs = ""
UDP_PORTs = 40002

socks = socket.socket(socket.AF_INET, # for Internet
                      socket.SOCK_DGRAM) # for UDP
socks.bind((UDP_IPs, UDP_PORTs))

# Port to send speed to door lock
UDP_IP_send = "192.168.1.140"
UDP_PORT_send = 40011

socksend = socket.socket(socket.AF_INET, # for Internet
                      socket.SOCK_DGRAM) # for UDP

##FUNCTIONS FOR THREADS
#function to connect to arduino and process gears
def connectSpeed(socka):
    #speed has to be global to be used in another thread
    global valKMH
    valKMH=0
    revsPC=0
    while True :
        data, addr = socka.recvfrom(1024)
        hiValRPM = (data[0])
        loValRPM = (data[1])

        #Revs : Mapping from 0-1023 to 0-6000
        if(hiValRPM == 0):
                revsPC = translate(loValRPM, 0, 255, 0, 1503)
        elif(hiValRPM == 1):
                revsPC = translate(loValRPM, 0, 255, 1504, 3004)
        elif(hiValRPM == 2):
                revsPC = translate(loValRPM, 0, 255, 3005, 4503)
        elif(hiValRPM == 3):
                revsPC = translate(loValRPM, 0, 255, 4504, 6000)

        #Speed : Mapping speed with gear value
        # 1st gear : 0-1023 to 0-20 km/h
        # 2nd gear : 0-1023 to 20-50 km/h
        # 3rd gear : 0-1023 to 50-80 km/h
        # 4th gear : 0-1023 to 80-110 km/h
        # 5th gear : 0-1023 to 110-160 km/h
        if(gear == 0):
                valKMH=translate(revsPC,0,6000,0,0)
```

```
        elif (gear == 1):
                valKMH=translate(revsPC,0,6000,0,20)
        elif (gear == 2):
                valKMH=translate(revsPC,0,6000,20,50)
        elif (gear == 3):
                valKMH=translate(revsPC,0,6000,50,80)
        elif (gear == 4):
                valKMH=translate(revsPC,0,6000,80,110)
        elif (gear == 5):
                valKMH=translate(revsPC,0,6000,110,160)

        valMPH = valKMH * 0.62
      print("RPM : " + str(round(revsPC,0)) + "   //     speed :
" + str(round(valKMH,0)) + "     //     gear : " + str(gear))

#function to get gears from socka
def connectGear(socka):
    #gear has to be global to be used in another thread
    global gear
    while True :
            data, addr = socka.recvfrom(1024)
            gear=bytes_to_int(data)


#function to send speed to doorlock
def sendSpeed(socka, IP, PORT):
    while True :
            kmhbytes = bytes(int_to_bytes(int(valKMH), 2)
            socka.sendto(str(int(valKMH)), (IP, PORT))

##DESTROY
def destroy(socka):
        socka.close()

##MAIN
if __name__ == '__main__':
        #defining the threads
        t2 = threading.Thread(target=connectGear, args=(sockg,
))
        t1 = threading.Thread(target=connectSpeed, args=(socks,
))
        t3 = threading.Thread(target=sendSpeed, args=(socksend,
UDP_IP_send, UDP_PORT_send,))

        try:
                t1.daemon=True
           t2.daemon=True
           t3.daemon=True
           t1.start()
                t2.start()
           t3.start()
                while True: time.sleep(100)
```

```
        except KeyboardInterrupt: # When 'Ctrl+C' is pressed,
the child program destroy() will be  executed.
            destroy(sockg)
            destroy(socks)
            destroy(socksend)
            sys.exit()
```

Light ECU

```
#!/usr/bin/env python

import socket
import RPi.GPIO as GPIO
import time
from time import sleep

TCP_IP = ''           # Keep this IP address
TCP_PORT = 40069
BUFFER_SIZE = 20      # Normally 1024, but we want fast response
GPIO.setwarnings(False)
GPIO.setmode(GPIO.BCM)       # Numbers GPIOs by physical
location
GPIO.setup(18, GPIO.OUT, initial=GPIO.HIGH) #Set LedPin mode
output

s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
while True:
      s.bind((TCP_IP, TCP_PORT))
      s.listen(2)
      while True:
            conn, addr = s.accept()
            try:
                  data = conn.recv(BUFFER_SIZE)
                  count = 0
                  conn.shutdown(socket.SHUT_RDWR)
                  if data == b'1':
                        print ("All Doors Locked", flush=True)
                        while count < 7:
                              GPIO.output(18,GPIO. LOW)
                              sleep (0.1)
                              GPIO.output(18, GPIO.HIGH)
                              sleep (0.1)
                              count = count + 1
                  elif data == b'2':
                        print ("All Doors Unlocked", flush=True)

                        while count < 5:
                              GPIO.output(18,GPIO. LOW)
                              sleep (0.1)
```

```
                    GPIO.output(18, GPIO.HIGH)
                    sleep (0.1)
                    count = count + 1

        elif data == b'3':
              print ("Drivers Door Unlocked", flush=True
              while count < 3:
                    GPIO.output(18,GPIO. LOW)
                    sleep (0.1)
                    GPIO.output(18, GPIO.HIGH)
                    sleep (0.1)
                    count+=1

finally:
      conn.close()
```

Appendix H CPU Bound Process Script

```
# importing the required module
import timeit

# code snippet to be executed only once
mysetup = "from math import sqrt"
for x in range(0, 100):
# code snippet whose execution time is to be measured
     mycode = '''
def example():
     mylist = []
     for x in range(1000000):
          mylist.append(sqrt(x))
'''

# timeit statement
     print (timeit.timeit(setup = mysetup,
                          stmt = mycode,
                          number = 1000000))
```